

**CNC MACHINE DESIGN FOR WHEELCHAIR USERS:
A CASE STUDY OF FADAL VERTICAL MACHINING CENTER 15**

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**CNC MACHINE DESIGN FOR WHEELCHAIR USERS:
A CASE STUDY OF FADAL VERTICAL MACHINEING CENTER 15**

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SUMMARY

Current survey has showed that most people with disability need equal work opportunity, while those with special needs may require special accommodations. Meanwhile, labor shortage is becoming more and more serious in existing manufacturing industry and there is less physical work involved in CNC machine operation. Thus it is a good opportunity for people with disability to work in manufacturing industry as CNC operators.

In the preliminary research, observation and interview were conducted to understand activities of FVMC 15(Fadal Vertical Machining Center is a type of CNC machine) operators. Operator's performance was restricted by the poor design of the machines and the work area and as a result, many people, especially wheelchair users face limited employment opportunities in the manufacturing industry. To address this problem, on we studied the workability of a current FVMC. For this, a full size FVMC was mocked up and 9 wheelchair users and 6 able-body users participated in this study. They were asked to mimic usability and tasks related to FVMC operation. This study also collected data for universal FVMC design. Based on this usability research, two concepts of FVMC design scenarios were developed and later the concepts were evaluated by two groups of users.

This study addressed limitations of wheelchair users with respect to CNC operation, especially reaching issues, and collected data about user needs and preferred FVMC settings for all users - wheelchair users and people without disabilities. Then, design guidelines were developed so machine engineers and designers could direct

attention to: 1) improve current designs of available FVMC for improved safety and performance; and 2) reconceptualize totally new designs of FVMC that through work reorganization offers very high level of safety and ease of operation for all users. The guidelines will increase direct design attention and produce better designs of FVMC and in turn the new machines will offer greater opportunities for employing wheelchair users alongside people without disabilities in the manufacturing industry.

CHAPTER 1

INTRODUCTION

Statement of Problem

Global competition and rapidly changing customer requirements have resulted in great changes in contemporary manufacturing. It is becoming increasingly important for manufacturers to use effective and efficient tools to increase productivity (Yan, 2003). One such tool is Advanced Manufacturing Technology (AMT), and a widely used example is CNC machine. The CNC machine stands for Computer Numerical Controlled Machine. It refers specifically to a computer that reads instructions generated by a processor and drives a powered mechanical device typically used to fabricate parts by removing material (Madison, 1996). The introduction of CNC machines into manufacturing industry fundamentally changed the work style and facilitated the operations; for example, the CNC machines make it easy to cut curves as straight lines and produce complex 3-D structures, thus dramatically reducing the number of machining steps that required human action (“CNC,” n.d.)..

These changes to manufacturing jobs come at the same time as changes to the manufacturing work force. The U.S is staring right in the face of a severe worker shortage as 77 million baby boomers prepare to retire in the next few years— with a fewer number of younger workers available to replace them. (U.S. Chamber of Commerce, 2006, p13). In a study funded by the National Association of Manufacturers (Eisen, 2003) more than 80 percent of the large and small manufacturers reported a

“moderate to serious” shortage of qualified job applicants, and forecasts predict a need for 10 million skilled workers by 2020 (National Association of Manufacturing, 2003)

One way to address this shortage of manufacturing workers is to consider people with disabilities for these positions. They make up a potentially large pool of workers. According to 1994–95 data from the National Health Interview Survey on Disability, 82.6% (489,000) of working-age wheelchair users are not in the labor force (Kaye et al, 2002). Nowadays, the societal trends also have made a shift from a medical model emphasizing a clinic approach of “fixing” or “curing” people with disabilities to the present emphasis on capabilities, choice, and workplace supports in maximizing the work potential of people with disabilities (Unger, 2002). Previous studies have shown that people with disabilities can utilize machines more effectively by enhancing job accommodations (Phillips et al, 1997). But currently, in manufacturing situations, wheelchair users are seldom employed as CNC machine operators.

Purpose of This Study

The purpose of this study is to create design guidelines and develop innovative concepts to improve CNC design and the operator’s performance, and make it more accessible to a wider range of CNC operators, including individuals with mobility impairment. The study focuses on a case study of a Fadal Vertical Machining Center (FVMC)--a type of CNC machine, and compares differences between operators with and without disabilities, finding out what accommodations or adjustments are needed to allow wheelchair users to successfully perform work tasks. This design can potentially create work opportunities for people with disabilities in an advanced manufacturing

environment.

For the purpose of this study, there are four steps:

1. Preliminary study: Use previously published research, and conduct interview and observation to define the need for CNC machine operators

2. Laboratory simulations: Evaluate existing machine to find out what are the barriers for operators using wheelchair

3. Design scenario evaluation: Evaluate two scenarios that utilize design and future technologies to develop a safe and efficient FVMC machine for wheelchair users and other people..

4. Provide design guidelines for CNC machine manufacturing.

Research Scope

Manufacturing, CNC machine, and people with disability are all big concepts. Manufacturing industries include food, beverage, textile, apparel, wood, paper, chemicals, plastics, rubber, machinery, electronic, etc.

CNC machines also have different types. Categorized by function, there are CNC routers, CNC lathes, etc. Categorized by shape, there are Vertical Machining Centers, Horizontal Machining Centers, and Table CNC machines. Different CNC machines are used in different manufacturing environments and have different requirements for the operator.

People with vision impairments, hearing impairments, mobility impairments, or cognitive impairments also have different limitations. Accommodations for them are quite different.

In this thesis, my research will focus on designs that may lead to work opportunities for wheelchair users in the metalworking manufacturing environment using Fadal Vertical Machining Center (FVMC) 15.

Metalworking

Metalworking is the craft and practice of working with metals to create individual parts, assemblies, or large scale structures. Originally, CNC was applied to metalworking machinery, and now the CNC machines are still mainly used for metalworking (James, 1996). Reported by the U.S. Census Bureau (2006), transportation equipment, computer and electronic products, machinery, food manufacturing, fabricated metal products, are top five manufacturing industries from 1994 to 2005 that employed more than one million workers in the USA. Four of these industries relate to metalworking.

Compared to working with big sheets of wood or steel, working with small-scale metal products requires less physical effort. Thus, these types of jobs might be easier for the wheelchair users to perform.

Fadal Vertical Machining Center (FVMC)

The Vertical Machining Center is one of the most popular CNC machine. It provides a wide power range for metalworking flexibility. Fadal Vertical Machining Center is deal for mold/die and other mid-range parts producers. It is advantage including:

- High level of automatic
- Combine multifunction
- Use for materials besides metal, (e.g. plastic)

FVMC (Figure 1) are being used in medical, mold /die, automotive, aerospace, heavy equipment and many other dynamic industries. Fadal has over 40 years of experience in the machine tool business. The Georgia Institute of Technology has two FVMC. One is in the Georgia Tech Research Institute machine shop, and is used for small volume production. The other is in the Manufacturing Research Center.



Figure 1: Fadal Vertical Machining Center 15

Wheel chair users

An estimated 1.6 million Americans residing outside of institutions use wheelchairs. The unemployment rate of wheelchair users is very high. (kaye et al., 2002)

Many people have mobility impairments, for example paraplegia or spinal cord injury; have to use manual or power wheelchairs. But their upper body may not be

affected, and they may have good muscle strength; and have finger, shoulder, elbow and wrist extension and flexion. This group of people may have the physical ability to work as CNC operators.

CHAPTER 2

BACKGROUND INFORMATION

People with Disabilities Need Equal Work Opportunities

Over half of the people with disabilities interviewed by Parent and her colleagues (1996) reported that they wanted to obtain a better job in the near future. According to Rehabilitation Research and Training Center on Disability Demographics and Statistics (2004), in the year 2004, only 22.4% of working age people with work disabilities worked full time full year. Because of their low employment rate, people with disabilities are more likely to be poor than those without disabilities. Within the working-age population (16-64), 30% of people with work disabilities live below the poverty level (LaPlante, Kaye, & Wenger, 1996). A series of studies conducted by the National Organization on disability and Harris (1998) found that an overwhelming majority (72%) of unemployed persons with disabilities indicated that they preferred to work.

“Putting people with disabilities back to work, or enabling them to remain at their jobs following onset of a disability, is one of the key elements of U.S. disability policy” (Kaye, 1998). The ADA, passed by Congress and signed into law in 1990, was designed to prohibit discrimination by private employers.

Current State of Manufacturing Jobs and Advanced Manufacturing Technology

More and more manufacturers are turning to the use of advanced manufacturing technology (AMT). Noori (1990) defined AMTs as new technologies which are used

directly by the firm in the production of a product. AMT utilizes the power of many new technologies, and particularly computers. The availability of computer power has had a significant impact on manufacturing. It led to the development of CNC (Computer numerical controlled) technology, robotics, and computer controlled handling devices, and increased the accuracy and flexibility of the manufacturing process (Sambasivarao & Deshmukh, 1995) It has also led to the integration of the product development and manufacturing engineering functions through the use of IT, which has had considerable impact on manufacturing in general (Sun, 2000). Real output per hour per worker in American manufacturing was more than four times greater in 2000, with the use of AMT, than fifty years earlier (Shapira, P., Youtie, J., & Urmanbetova, A 2004). With regards to occupational health, stress and safety matters, Advanced Manufacturing Technologies obviously have good effects, including decreased physical load and less exposure to environmental factors (Seppala & Tuominen, 1992).

Cognitive and Physical Requirements of CNC Occupations

Many CNC machines can almost run unattended during their entire machining cycle, freeing the operator to do other tasks. This gives the CNC user several side benefits, including reduced operator fatigue, fewer mistakes caused by human error, and consistent and predictable machining time for each work period (Madison, 1996). Since the machine runs under program control, the skill level required of the CNC operator, which is related to basic machine practice, is also reduced as compared to machinists producing work pieces with conventional machine tools (Pabla & Adithan, 1994).

In addition to the traditional machinists' skills, working with CNC machines calls

for programming, and manipulation of processing schedules and pallet storage via a terminal. Some advertisements on the Internet for CNC machine operators in metalworking manufacturing environments listed the following requirements and tasks:

- Be capable of handling 5lb, to 200lb with the assistance of hand trucks, lifts, conveyors and hoists.
- Be able to stand for long periods up to eight or more hours.
- Clean and maintains machine, tooling, and parts to maintain equipment in optimal production condition.
- Inspect cutting tools for sharpness and usability.
- Inspect work pieces throughout the production run.
- Work in teams to troubleshoot manufacturing problems and perform quality assurance checks of work.

It was believed that human operators would be replaced by pre-programmable computerized systems run by technical specialists (Bullinger, Warnecke & Lentz, 1983). The operators' role was supposed to be limited to performing only monitoring tasks. But for now, automation in manufacturing is progressing in small steps (Seppala, 1992). Even though CNC machine design has progressed significantly over the past 20 years, two problems exist that require attention: 1) workers are assuming forward-leaning postures, and 2) these postures are usually unsupported. To make matters worse, many of the same workers who must perform their work in forward-leaning postures must do so for long periods of time. (Vieira & Kumar, 2007). Bending, twisting, lifting heavy weights, and making forceful movements have been shown to be related to work-related low back disorder (Frymoyer, 1980).

Precedence of People with Disabilities Working in Manufacturing

The use of AMT clearly has the potential to increase productivity in the manufacturing environment. This technology also has the potential to significantly reduce the physical and sensory demands on manufacturing employees (Campbell, et al., 1990, pp363-371). The existence of computer controlled equipment (e.g. CNC) is an essential aspect of advanced manufacturing technology (Bayo-Moriones & De Cerio., 2004). These changes provide opportunities for people with disabilities to work in manufacturing. “In fact, some facilities that currently employ a significant number of people with sensory disabilities in manufacturing are using advanced manufacturing technology to help them remain competitive in the market place” (Haynes & Sarah, 2005)

It is known that many products are not accessible to large sections of the population. Designers instinctively design for users without disabilities and are either unaware of the needs of users with different capabilities, or do not know how to accommodate their needs into the design cycle (Keates & Robinson, 2000). The CNC machine is one of those products. But now, some efforts already are being made to put people with disabilities into manufacturing environments as CNC operators. One successful sample is the Seattle Lighthouse. The majority of Seattle Lighthouse operations are self-funded through manufacturing and sales of products to customers, including the Boeing Company and the federal government. Large numbers of people with disabilities work in their manufacturing facilities: of approximately 175 employees with sensory disabilities. People with disabilities fill a wide range of positions, including CNC operators. Seattle Lighthouse has been in existence for almost a century. Their products are competitive in the market.

Making CNC operator jobs accessible to people who use wheelchairs, however,

will require some changes to the workstations. A previous study by Nowak (1989) on the anthropometric investigation of people with a mobility-related disability concluded that there were significant differences in functional arm reach between the people without disabilities and disabled population. This difference indicated a need for a different layout of workspace for individuals with functional limitations in their motor efficiency (Babski-Reeves, 2005). Based on the results of this study, work area layout and design characteristics are important and critical factors that must be considered in this study.

CHAPTER3

PRELIMINARY STUDY

Findings from this study provided information to prepare full-size FVMC mock up testing and were used to generate design scenarios.

Research Questions

RQ1: What are the most important tasks are for FVMC machine operators?

RQ2: What are the potential problems that a wheelchair user might encounter?

Research Methods

There were two phases to the preliminary study. First, there was a structured interview with CNC operators who explained their work and tasks. During the second phase, the researcher shadowed the FVMC operators to observe them while they were working. All the information from this study with operators was brought together and compiled with the literature review, resulting in developing an understanding of work experience and needs for wheelchairs users

Interview

Structured interviews were conducted to better understand FVMC operators' experiences and responsibilities. Subjects were asked about 1) their education and how they were trained as a CNC operator; 2) their job duties, including tasks that were difficult for them or had safety ; 3) suggestions for people with disabilities who are interested in

becoming CNC (FVMC) operators in the manufacturing environment. The interview questions are listed in Appendix A. They are also courage to talk about any information about CNC machine. Their responses were recorded by notes (see Appendix B), and compiled later.

Five people were interviewed. A FVMC operator with 24 years experience working in metal working manufacturing was interviewed in Georgia Tech Research Institute (GRTI). A CNC operator with 26 years experience working with different kinds of CNC machine including FVMC and a student now using FVMC machine are interviewed in Manufacturing Research Center (MRC). In order to get more information, another 2 CNC operators in Purdue University were interviewed by telephone.

Observation

Two observations were conducted in GTRI. The operators were asked to do their daily work twice. First, the operators were asked to do their work as usual. The second time, some operational questions were asked while the operator was working on the FVMC machine. For example: What are you doing now? Which task can be simplified by the existing technology? Which tasks do you need to do all by yourself? The operators usually stopped and repeated the tasks to make sure the researcher understand the process. After the observation, the machine components were measured carefully.

Finding and Insight

CNC machine developed for more than 30 years. The capability of CNC machine enhances, but ergonomic problem of machine design relate to the tasks (Many tasks require operator to lean forward, twist and reach high, this will cause discomfort, fatigue and psychological stress) still exist.

Although CNC is widely in used by people without disabilities, it has been shown that users with disabilities person face difficulty in operating CNC.CNC machine especially the FVMC is only designed for the operators work standing up.

Finding:

A workflow chart (Figure 3) was constructed after the observation.

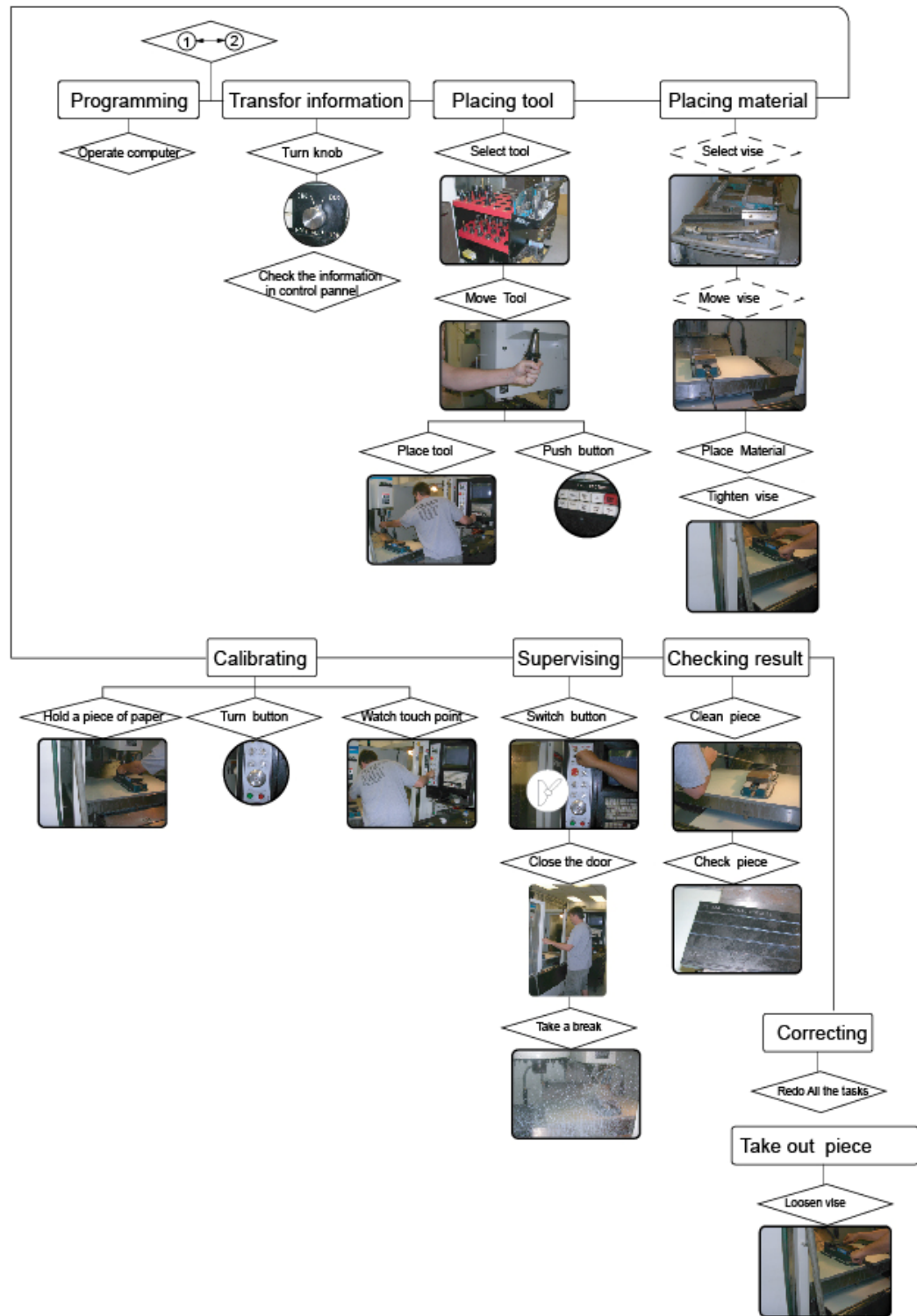


Figure 2: FVMC Operation Work Flow

CNC operators' duty is programming, setting up the machine, loading/unloading materials, calibrating, controlling quality, cleaning and maintaining machine, but it depends on the size of manufacturing. Technologies simplify the working process: some complicated tasks can be finished by just push a button. For example, calibrating used to be a complicated process, but now using "edge finder" it can be finished by push button. The operators interviewed used to working in small manufacturing. They need to work independently to finish most of their work. Specific main tasks required for most FVMC operators to finish independently very often include:

- Loading/unloading Material (Figure 3): The operator needs to pick a piece of material from the table next to FVMC machine. A handle is used to tighten the material.
- Operating the control unit (Figure 4): The operator reaches the upper area to adjust the movement of cutting tool; reaches the lower area to start and stop machine; types on the keyboard area to input commands. Commands is read on the screen of control unit.
- Remove and replace dull cutting tools (Figure 5). Dull tools will decrease the accuracy of use. The operator inserts the tool into the tool holder; holds the tool and reaches the "Tool/In Out" button to replace cutting tool.
- Measure the work piece to check the accuracy of their work. Measuring tools needs to be used (Figure 6).



Figure 3: Observation of a FVMC operator loading material



Figure 4: Observation of a FVMC Operator Operate on the Control Panel



Figure 5: Observation of a FVMC Operator Changing Dull Cutting Tool



Figure 6: Observation of a FVMC Operator Measuring machined part

The biggest problem for wheelchair users to use this machine is “reach” problem, if every component interacted with the operator is within the reach range of wheelchair users, FVMC can be used by wheelchair users. Based on this finding hypothesis were generated for next step of study. The proportion and dimension of CNC machine should be redesigned to enable operators (including people without disabilities and people with mobility impairment) to adopt as close to optimum posture as possible during machine operation. Position of control panel and machine table should be adjustable, and tool holder also needs to be adjustable in the horizontal direction. Two hand works should be avoided, except for the keyboard. Figure 7 shows the existing FVMC with accommodations might be able to be used by the wheelchair users.

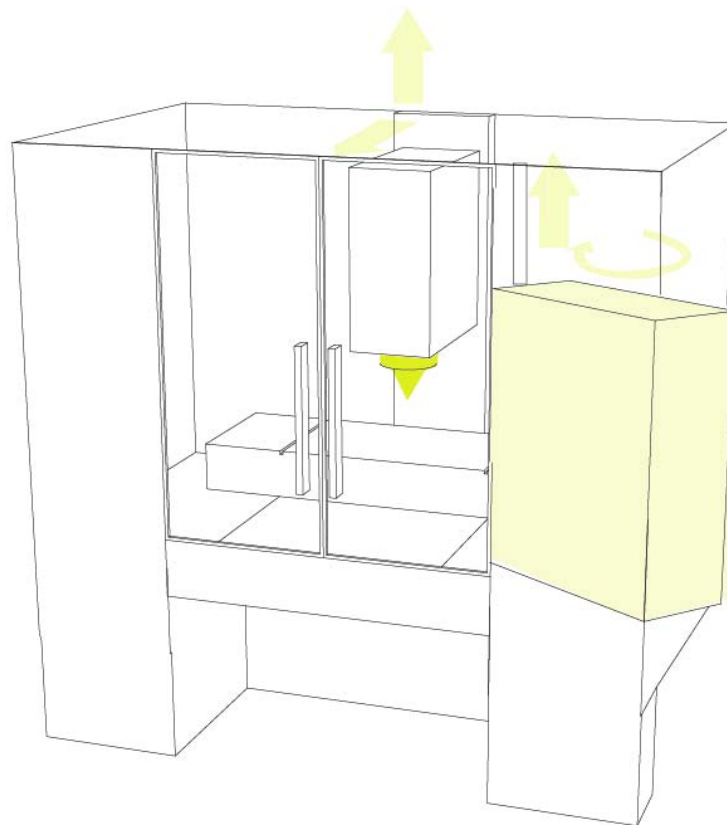


Figure 7: Design Sketch of FVMC Based on Existing Technology

Insight

Insights from the interview and observation provide information for the future FVMC design and future work of my study.

- Operational requirements:

- Operators should enhance productivity, working efficiently
- Operators sometimes should be able to work on several machines.
- Operators have wide range of responsibility. They are involved in programming, operating, supervising, and cleaning and maintaining machine.

- Operator's discomfort and safety issues:

- A lot of movements are involved in the workflow. The environment and route of the workflow is shown in Figure 8, an operator use the desktop in the computer room to finish the CAD drawing and programming, then he sends the file document through the Internet to the CNC machine in the work shop. ③ is a tool room next to the work shop.

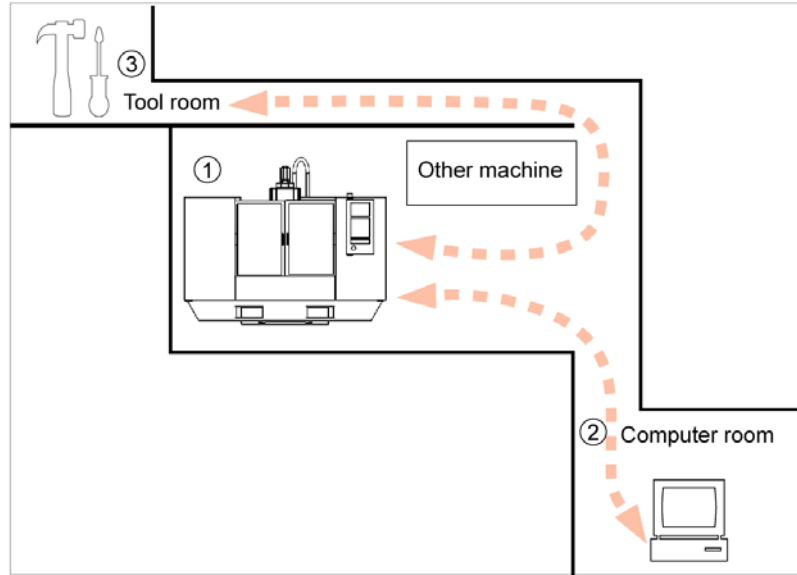


Figure 8: Layout and Route in the CNC Machine Environment.

- Besides operate on the machine, FVMC operators also use hand tools quite often, such as screw driver, Allen-wrench to help with the work. It will require movement of the operator in the workspace to get those tools. Considering the way how arranging the machine can reduce the movement.
- Loading/unloading material and clean are the tasks causing discomfort. Sometimes this task even causes injury.
- Ergonomic problems of machine design relate to the tasks (Many tasks require operator to lean forward, twist and reach high, this will cause discomfort, fatigue and psychological stress). Leaning forward into the machine and standing for 8 hours cause their fatigue.
- Using the mouse on the control panel is uncomfortable.
- An operator is hit by the flying chips, because he forgets to close the protective window,

or the window is not completely closed.

- Operators also concern about the damage on the machine, because fixing the CNC machine is expensive. Cutting into the table, damage on the tools, window broken by the moving vise happen to the FVMC. Accidently stopping the machine by push wrong button on the control panel also cause break the drill and scrape the work piece.

- *Design consideration*

- Difficult to see the scale on the switches, some of switches, knobs and buttons look quite similar, easy to be misused by the operator; label on the frequently used buttons wear off.
- The view of production process is limited by flying chips and cooling lubricants
- After the machines are set up, running CNC to machining a part only takes 5 minutes; CNC operators usually have to work 8 hours per day, so they repeat the same activates more than 50 times a day. They are easy to get bored. Attractive things work better (Dorman, 2002), comparing with the first generation CNC machines, the CNC machines now we used are not quite different. If new design of machine can be attractive, it may keep operators exiting and more concentrate on the work and enhance productivity, and reduce accident.

- *Consider the operator using wheel chair*

- Some operators suggest that the future machine should be more compact, combining more function in a machine. Technology existing and coming in near future can impact the wheelchair user's performance as a FVMC operator: Wearable computer, Remote

controller, “R2D2” tool cart, Robot friend assistant, Vise with sensors and self adjusting, temperature sensor, coolant flow control, voice control

- All of the FVMC operators interviewed think the CNC operator is a difficult job for wheelchair users. Reaching and observation is the big barrier for people with wheelchairs.
- FVMC is designed for the operator work standing up, many tasks required operators reaching high, reaching forward, reaching two side. These tasks might be the barriers for the wheelchair users who want to be FVMC operators.
- The tool carts will disturb operator’s movement. The work area should be rearranged to reduce the movement.

CHAPTER 4

LABORATORY SIMULATIONS

In order to design a new design of a FVMC used by people with and without disabilities, it was important to identify problems they experience with using them, and redesign a machine to meet their physical and operational needs. This part of the study included people with and without disabilities to demonstrate the simulated of a FVMC, using a non-working model that was derived from the existing designs of CNC machines (see Figure 9).



Figure 9: Full size FVMC mock-up

For safety of the participants, the model did not have any moving parts, and participants did not have any danger of using it. A total of 15 adults participated in the study, which included six people without disabilities and nine wheelchair users. Participants interacted with the machine and acted out the process of manufacturing an item as it happens in a production situation. The process was videotaped to study operational issues, and Participants were interviewed to learn how size, shape and design features of the CNC machine promoted easy use or presented difficulties, and to identify areas in which design improvements were needed

Research Questions and Hypotheses

There are 2 main research questions for this study:

RQ1. What are the main barriers for wheelchair users in the FVMC operation workflow?

H1. Existing CNC (FVMC) is difficult to use by people with mobility impairment

H2. The behavior and preference between wheelchair users and people without disabilities are different.

RQ2. How to overcome those barriers?

H3. Customization of the following will improve the usability of a CNC (FVMC) for wheelchair users

- Increased space under the working table
- Inclusion of an adjustable tool holder

- Inclusion of a height adjustable control panel

H4. If the FVMC design remove the “reach” barrier, people with mobility impairment can work on the CNC machine efficiently, as comfortable as people without disabilities.

Research methods

Subjects

This part of the study recruited 15 subjects -- nine people with mobility impairments who used wheelchairs, and six people without disabilities. Subjects with disabilities were recruited through the CCN (CATEA Consumer Network), disability-issue oriented support groups, healthcare providers, and disability and rehabilitation organizations. Non-disabled participants were recruited via email to the GT student and faculty population, and by word of mouth.

Age: The subjects were aged 18-64, working age. Six of them were age 30-40; six were age 18-30; three were 40-50 years old.

Gender: Only one female wheelchair user and only one female without a disability were included in this study. At the beginning, the researcher anticipated an equal number of both genders, but it was very difficult to find female participants.

Education: Most of the subjects had high education. Four of the subjects had master’s degrees (27%), five were graduate students (34%), and the others had graduated from high school.

Disability: Most of the individuals in the study had used a wheelchair for many

years. Five participants had spent more than 10 years in a wheelchair. Three of the wheelchair users had a Spinal Cord Injury in C6-8. That means they did not have full hand function. Some of them could not move 2-3 fingers; some of them could not lift anything heavier than 5lb with one hand. The other subjects were all paraplegics at level of T10 or below and had full hand function and good trunk stability with the ability to lean forward and side-to side without loss of balance. One non-disabled subject who was familiar with the machine shop and people with disabilities simulated a T10 level wheelchair user and completed the tests while seated in a wheelchair. So in my study, 10 people in wheelchairs were tested.

Job: Only three wheelchair users didn't have a job, and they indicated it was because of poor design of the environment. Two wheelchair users who participated in this study had CNC machine operation experience; four non-disabled participants had this experience.

Information about the subjects' age, gender, and disability, type of wheelchair, education, employment, and CNC experience is listed in table 1.

Table 1: Description of Participant Population

No	Age	Type of Wheelchair	Gender	Disability	Education	Job	CNC experience
1	30-40	Power	F	SCI T10*	1 year college	No	No
2	30-40	Power	M	SCI C7**-C8	1 year college	No	No
3	30-40	Manual	M	Spine Bifida	Graduate student	Full-time	Yes
4	18-30	Power	M	SCI C6	1 year college	Part-time	Yes
5	40-50	Manual	M	Paraplegia	Graduate degree	Full-time	No
6	40-50	Power	M	SCI C7-C8	High school	No	No
7	30-40	Manual	M	SCI T12	Graduate degree	Part time	No
8	18-30	Manual	M		Graduate student	Full-time	Yes
9	30-40	Manual	M	Paraplegia	Graduate degree	Full-time	No
10	30-40		M	Paraplegia	High school	Full-time	No
11	18-30		M		Graduate student	Part-time	Yes
12	18-30		F		Graduate degree	Full-time	No
13	18-30		M		Graduate student	Part-time	Yes
14	18-30		M		Graduate student	Part-time	Yes
15	40-50		M		Tech School	Full-time	Yes

No.1-10 are “Wheelchair User”(WU), No.11-15 are People without disabilities (PWD)

*T10 represents spinal cord injury at tenth thoracic vertebrae

**C7 represents spinal cord injury at the seventh cervical vertebrae

Procedure

Mock-up making

The full size CNC mock-up was made of wood, foam-core, 80/20 parts, and a height adjustable table (Figure 10). Each component relating to the work tasks was adjustable. Measuring devices were attached to the structure (Figure 11), so the researcher could easily record measurements.

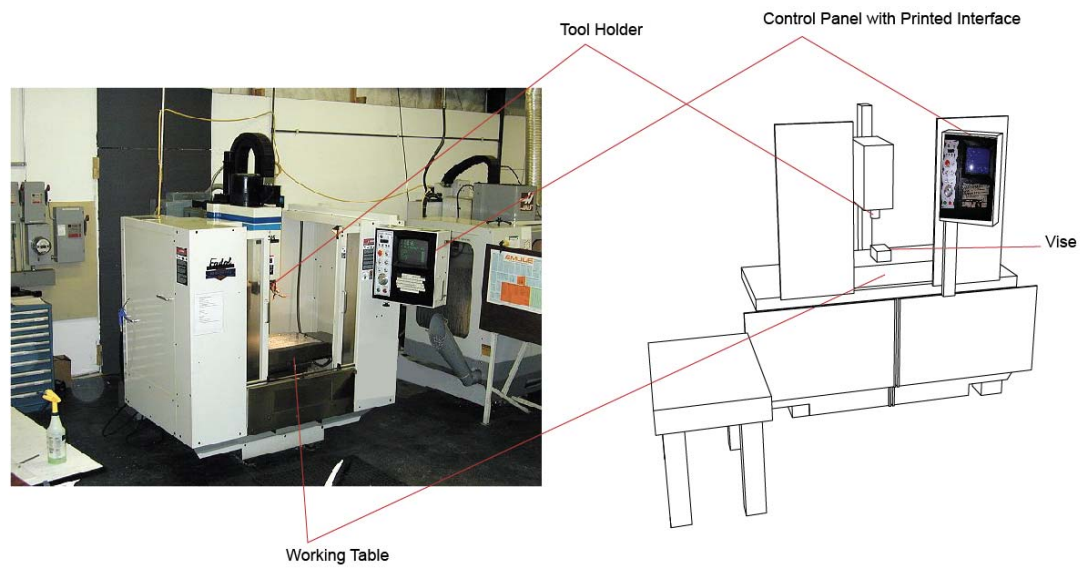


Figure 10: Structure of FVMC Mock-up



Figure 11: Each Component on Mock-up Related to the Work Tasks was Adjustable

Tasks for Prototype Testing:

Before the testing started, the subjects were given instructions about the tasks.

Four main tasks related to the FVMC (CNC) operation performed by the subjects are listed below:

Loading/Unloading Materials

1. Pick up any one of the three piece of material located on the left side and move the material to the machine table (Figure 12).
2. Place the material on the table marked “VISE” (Figure 13).
3. Pick up the handle next to the material and insert the handle onto the vise. Rotate the handle to tighten the vise on the table (Figure 14).



Figure 12: Pick Up Any one of the Three Pieces of Material

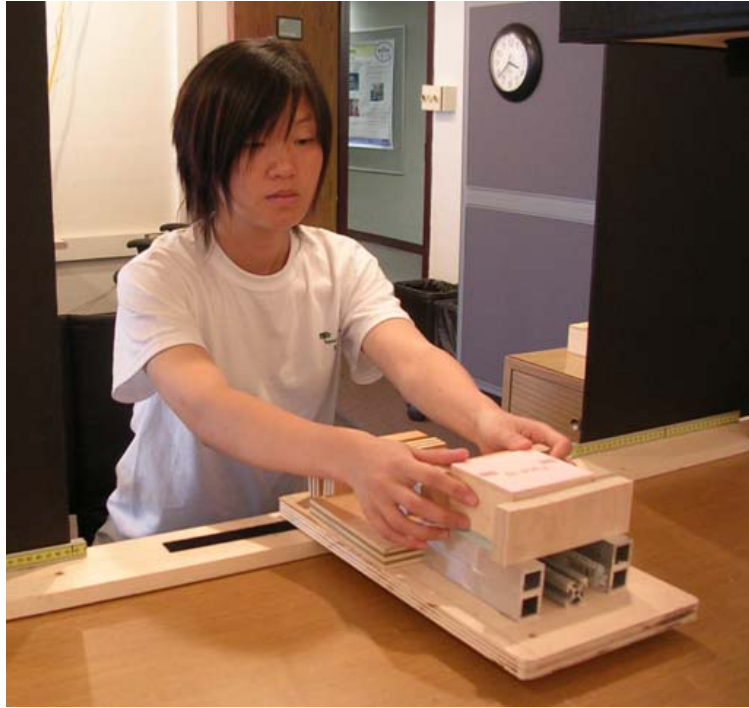


Figure 13: Place the Material on the Table Marked “VISE”

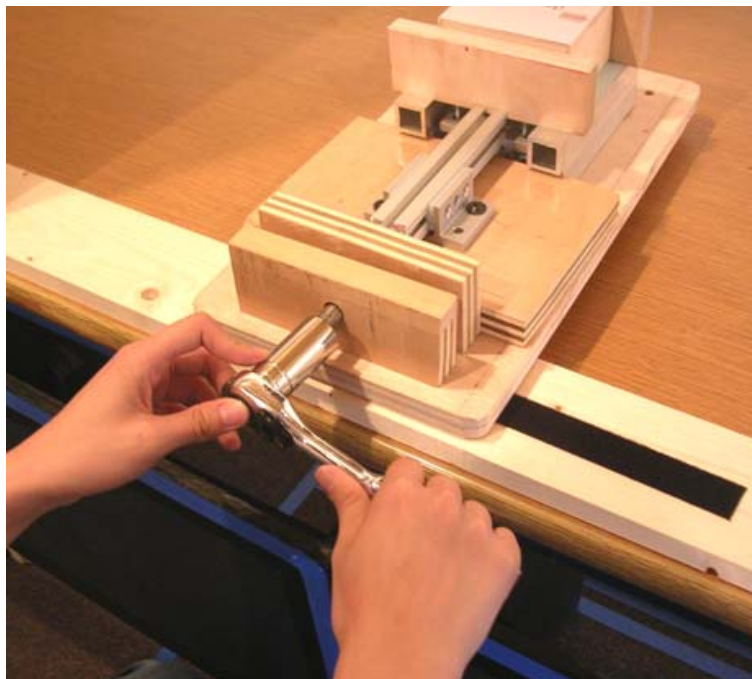


Figure 14: Tighten “Vise”

Operating on the Control Panel

4. Pretend to operate the control panel to the right of the user by touching all the upper buttons.
5. Pretend to operate the control panel by touching all the lower buttons.
6. Pretend to type on the keyboard in the control panel (Figure 15).
7. Read the sentence on the “screen”.



Figure 15: Pretend to Work on the Control Panel

Replacing Dull Tool

8. Pick up the cylinder from the desk on the left and put it in the hole of the tool holder located above the “VISE” (Figure 16)
9. Hold the tool and touch the “pink button” on the control panel (Figure 17).



Figure 16 : Pretend to Insert a Tool into the Tool Holder



Figure 17: Hold the Tool and Touch the Pink Button on the Control Panel

Checking Machined Part

10. Use tape measure to measure the width and length of the block (Figure 18).

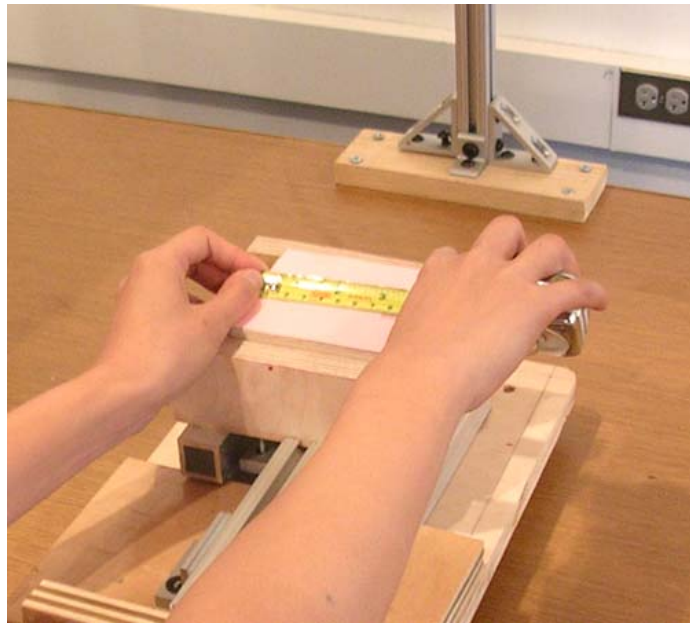


Figure 18: Use Tape Measure to Measure the Width and Length of the Block

Settings for Prototype Testing

The wheelchair users were asked to perform the same tasks on three settings (Setting1, Setting 2, and Setting 3) of the FVMC machine mock-up. Able-bodied participants were asked to perform the same tasks on four settings (Setting 1, Setting 2, Setting 3, and Setting4) of the FVMC machine mock-up.

Setting1 (S1)-Current design (Figure 19): Based on existing machine, each component is in the same position as FVMC 15



Figure 19: FVMC Mock-up Setting One

Setting 2 (S2) - Settings based on ADA regulation (Figure 20): The mock-up was adjusted to accommodate wheelchair users. There was a space of W30"xH27" inches under the machine working table, and the tool holder was within the D20x H48 inches reaching zone of wheelchair users. Height from floor to the center of the screen on control panel was 47.1 inches to match data of average eye height (Das & Kozey, 1999).



Figure 20: FVMC Mock-up Setting Two

Setting 3(S3) - User Preference (Seated): In this setting, Participants were asked to adjust the machine to their preference (Figure 21). Wheelchair users worked with the mock up while sitting in their wheelchairs. Able-bodied subjects worked with the mock

up while sitting on a height adjustable chair.

Setting 4 - User Preference (Standing): In this setting, the able-bodied participants were asked to adjust the machine to their preference, when they worked standing up.



Figure 21: FVMC Mock-up Setting 3

Questionnaires and scales used

Demographic and anthropometric information

using standard tools such as a flexible tape measure or caliper. For five subjects without disability, eye height and shoulder height was measured twice--when they were standing and when they sat down on a height adjustable chair. They were

asked to adjust the chair to the most comfortable height and keep their thigh flat.

Dimensions on each setting were collected prior to the test session. Data collected on the participants while they were performing each task included loading/unloading material, operating the control panel, changing tool, measuring finished part. After they finished performing each task, a questionnaire was filled out by the researcher or participant. Participants randomly worked on the two setting and performed four simulated FVMC operation tasks in a laboratory. At the end of the study, a short interview was conducted, and subjects were asked about the use of the FVMC model, and how it was set up, what they liked best, and why. The act of operating the FVMC mock-up was videotaped, using overhead cameras. Prior to the testing session, a questionnaire (Appendix E) was administered to collect subject background and demographic information. After that, the subject's stature, eye height, knee height, shoulder height, elbow height and arm length were measured

Task Performance Difficulty

The participants were given six options for rating their physical ability to perform each of the tasks. The options were: 0=I can't do it; 1=Very Difficult, 2=Difficult, 3=Just Right, 4= Easy, 5= Very Easy (Figure 22). Thus, higher scores meant that the task was easy to perform. The full "Tasks Difficulty Evaluation Form" is listed in Appendix G.

■ *Tasks Difficult V.S Easy Evaluation Form*

	0	1	2	3	4	5
Tasks	Can't Do It	Very Difficult	Difficult	Just Right	Easy	Very Easy
Pick up the cylinder at the desk on your left and position it in the hole located above the block	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Hold the tool and touch the red button on the control panel	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 22: Task Difficulty Evaluation Form and Scale

Machine Component Position Evaluation

Work area layout and design characteristics were evaluated to determine if the machine dimensions and FVMC mock-up components' position were appropriate for the participant's ability. As shown in Figure 23, subjects marked one of seven options to report whether the component was too high, too low, or just right. For example if the subject felt the tool holder was too high, he could mark the result as “-3”.

■ *Machine Components Evaluation Form*

	-3	-2	-1	0	1	2	3
The tool holder is	Too High <input type="radio"/>	<input checked="" type="radio"/>		Just Right <input type="radio"/>			Too Low <input type="radio"/>
The tool holder is	Too Far <input type="radio"/>			Just Right <input checked="" type="radio"/>			Too Close <input type="radio"/>
The control Panel is	Too Far <input type="radio"/>			Just Right <input type="radio"/>		<input checked="" type="radio"/>	Too Close <input type="radio"/>

Figure 23: Machine Components Evaluation Form and Scale.

User Preference Comments:

At the end of the evaluation, subjects were asked to verbally comment on the features, comfort, likes, dislikes, or anything else regarding to the testing. Comments were recorded onto a Microsoft word document by the researcher as the comments were made. The evaluator immediately edited the comments after the subjects finished the testing.

Results

Anthropometry measurements are listed in Table 2.

Table 2: Anthropometry measurement of subjects

No	Seated Measurement(cm)					Upstanding Measurements		
	Stature	Eye Height	Shoulder Height	Knee Height	Arm length	Stature	Eye Height	Shoulder Height
1	126.5	115.7	100.5	67.4	61.6			
2	142.9	134.2	109.4	75.7	69.7			
3	130.1	112.8	97	59.3	64.5			
4	138.9	124.5	108.1	67.7	63.5			
5	142.8	131.2	109.8	67.9	70			
6	141.5	125.2	115.3	71.1	61.5			
7	138.6	84.9	109.2	67.9	71.3			
8	136	123.3	107	64.1	68.8			
9	129.4	117.3	97.4	60.1	58.6			
10	136.2	124.6	105.5	65.9	67.4			
11	130	118.9	99.6	59.9	64.5	177.9	164.8	143.9
12	118.5	107.9	90.9	55	50	157	139.8	121.8
13	127.5	115.2	96.6	55.6	61.2	172.3	162	140.1
14	133.8	121.4	105.3	58.8	60.1	181.3	169.9	151.3
15	132.8	118.6	99.2	61.3	61.8	184.8	172.4	153.3

Data analysis:

Respondents reported their level of difficulty performing each of ten tasks in each machine setting. Higher task difficulty scores meant the tasks were easier for the participants in their perspective.

Independent samples t-tests were used to compare the task difficulty responses between subjects who used wheelchairs and subjects without disabilities. Paired samples t-tests were run to compare the scores for same group of subjects on different settings.

Comparison on Setting 1 (S1)

Figure 24 shows the performance difficulty ratings for the machine set up to match current designs. All of the tasks are easy for people without disabilities to do on the machine setup to match user preference, but a lot of tasks are difficult for wheelchair users.

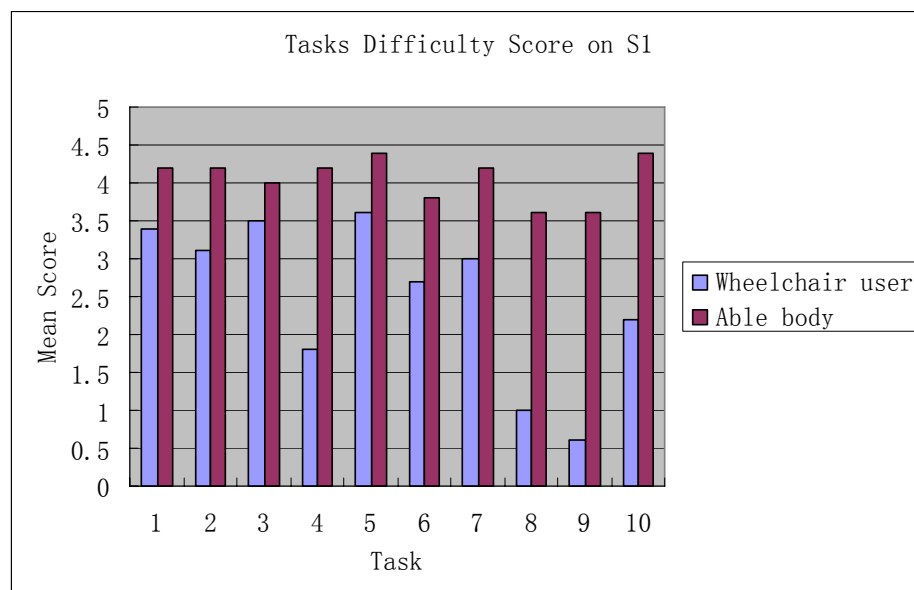


Figure 24: Task Difficulty Score on S1

The following tasks received scores under 3.0 (difficulty “just right”) for wheelchair users: Task 4 - touch all upper buttons (on the control panel), Tasks 6-Touch Keyboard, Task 7- Read the sentence on the “Screen” Task 8 - pick up the cylinder and position it in the tool holder hole; Task 9 - hold the tool and touch the pink button on the control panel; and Task 10 - use tape measure to measure the width and length of the block.

Independent samples t-tests were run to compare the scores for each task between the wheelchair users and able-bodied people. Table 3 shows that there was a statistically significant difference for tasks 4, 8, 9, and 10 ($p > 0.05$).

Table 3: T-Test Result of Comparing Task Easy Level between WU and AP on S1

Task	t	P
4	-7.532	0
8	-5.643	0
9	-4.461	0.001
10	-3.533	0.004

From the “Machine Components evaluation form” (Table 4) we learn some of the important reasons for the difference between Wheelchair Users (WU) and People without Disabilities (PWD) subjects. Numbers close to zero represent a component position that is “just right.” Negative numbers down to -3 represent components that were “too high” or “too far”; numbers up to +3 represent components that were “too low” or “too close.”

The findings show that the control panel is too high and too far from the operator, and the tool holder is too far for wheelchair users.

Table 4: Means of S1 Machine Components Evaluation score for Wheelchair users

Machine Components Evaluation (S1)	Mean (WU)
The table on the machine	-0.1
The window opening	-0.7
The control panel(Height)	-2.6
The control panel(Distance)	-1.9
The tool holder(Distance)	-2.8

Comparison of Machine Settings for Wheelchair Users: S1 and S3

In S3, machine components were adjusted and wheelchair users were asked to perform the same task again. Figure 25 shows the performance difficulty rating for wheelchair users on machine set up to match current designs and user preference. All of the tasks are easy on machine set up to user preference. Some of the tasks are difficult on machine setup to current design.

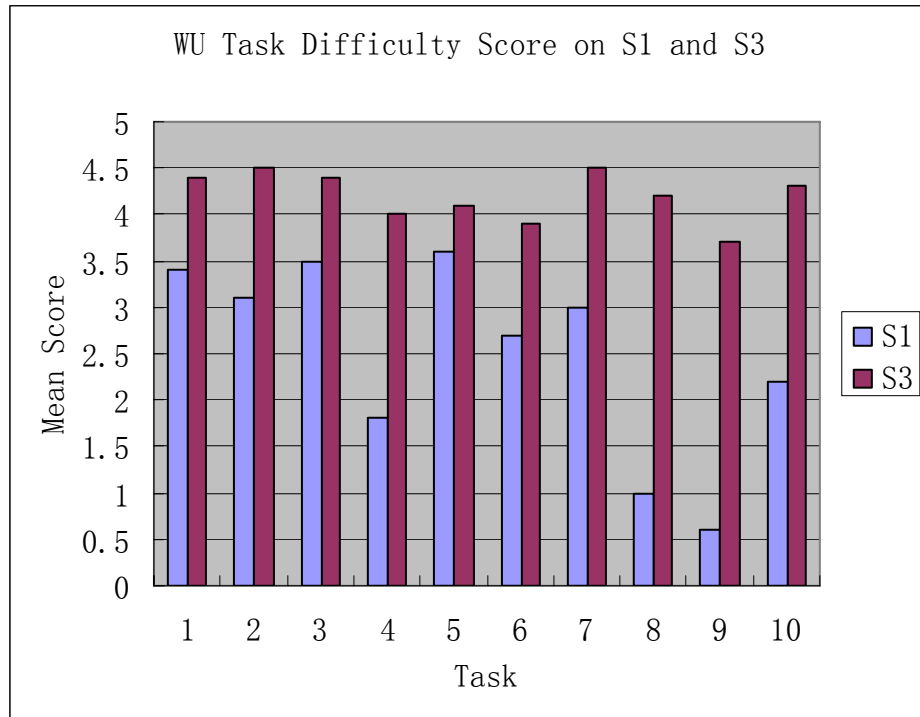


Figure 25: WU Task Difficulty Score on S1 and S2

No tasks received scores under 3.0 for wheelchair users on the machine setup to match their preference. Tasks 4, 6, 7, 8, and 9 on machine setup match current designs received scores under 3.

Paired samples t-tests were used to compare the scores for these two setups of prototype. Table 5 shows that there was a significant difference for Tasks 4, 8, 9 and 10 ($p > 0.05$)

Table 5: T-Test result of Comparison WU Task Difficulty Score on S1 and S2

Task	t	P
4	-9	0
8	-7.236	0
9	-5.894	0
10	-4.846	0.001

On the machine set up to the preference of wheelchair all of components position scores were 0. As Fig 25 shows, after making accommodations to the machine, participants rated all of the tasks as easy.

Comparison of Machine Settings for People without disabilities: S2 and S3

Figure 25 shows the performance difficulty rating for people without disabilities on machine setting based on ADA regulation and setting matched user preference seated. All of the tasks are easy for people without disabilities on the machine set up to user preference. Some of the tasks are difficult on machine set up to current designs.

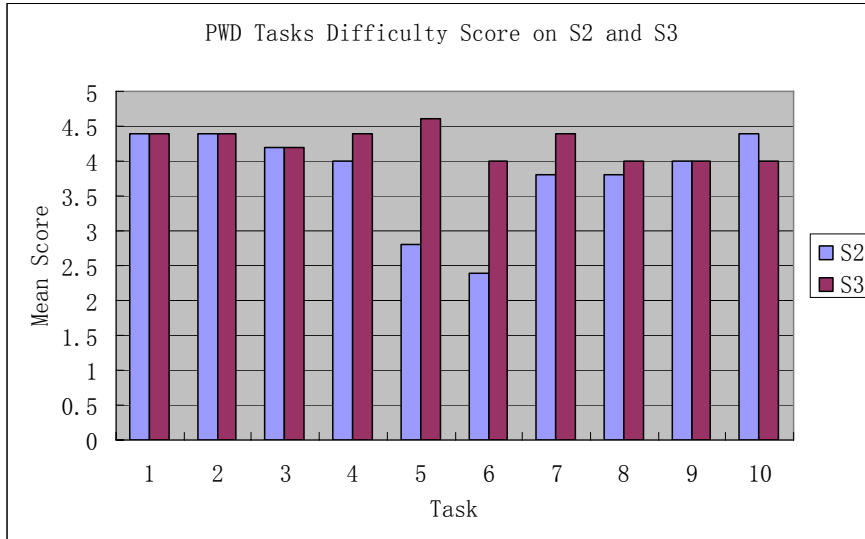


Figure 26: PWD Tasks Difficulty Score on S2 and S3

The following tasks received scores under 3.0 for people without disabilities:

Task5-touch lower buttons, Task6-touch keyboard

Paired samples t-tests were used to compare the scores for these two setups of prototype. Table 6 shows that there was a significant difference for Tasks 5 and 6 ($p > 0.05$)

Table 6: T-Test Result of compare PWD Tasks Difficulty Score on S2 and S3

Task	t	P
5	-3.674	0.021
6	-3.138	0.035

From the “Machine Components evaluation form” (Table 7) we learn some of the important reasons for these two settings. The findings show that the window opening is too wide and the control panel is too low on the machine setting based on

ADA regulation. On the machine set up to the preference of people without disabilities standing, except two subjects indicated that the machine table is not lower enough, all of components position scores were 0. They indicated if the machine table can be 1” lower, it will be just right. As Fig 26 shows, after making accommodations to the machine, participants rated all of the tasks as easy.

Table 7: Means of S2 and S3 Machine Components Evaluation score for PWD

Machine Components Evaluation	Mean (S2)	Mean (S3)
The table on the machine	0.8	-0.6
Space under the table	0	0
The window opening	1.8	0
The control panel (Height)	0.4	0
The control panel (Distance)	1.4	0
The tool holder (Distance)	0	0

Comparison on Setting 3 (S3)

In Figure 27 shows the performance difficulty rating for the machine set up to match user preference. All tasks are easy for people with and without disability.

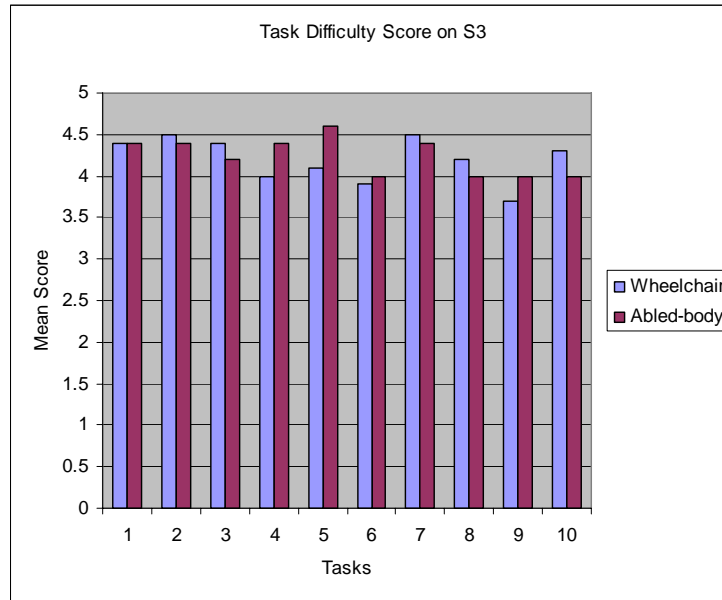


Figure 27: Task Difficulty Score on S1

Independent samples t-test were run to compare the scores for each task between the wheelchair users and people without disabilities. Table 3 shows that there was no statistically significant different for all tasks. Except two subjects without disability indicated the machine table needs to go down one inch. All of the components were just right.

Table 8: T-Test Result of Comparing Task Easy Level between WU and AP on S3

Task	t	p
1	0	1
2	0.276	0.787
3	0.393	0.7
4	-0.91	0.38
5	-1.254	0.319
6	-0.144	0.888
7	0.237	0.816
8	0.425	0.678
9	-0.455	0.657
10	0.621	0.545

Adjustment range of machine components

Range and median of each component on the FVMC are listed in table 9:

Table 9: Range and Median of FVMC 15 Components

Component	Adjustment Range (cm)	Median (cm)
Height of the machine table	71.7-81.1	78.9
Width of the space under the table	78-110.5	78
Depth of the space under the table	38.1-48.3	39.4
Window opening (left side)	34.5-53	51
Window opening (right side)	34.5-52.5	51
Position of the control panel (from center of machine to the pivot of the control panel)	62.5-83	69.3
Height of the control panel	61-118.8	75.3
Angle of the control panel	75-90	90
Position of the tool holder	17-53.8	28
Height of the tool holder	100.6-153	122.85

Other finding:

Wheelchair users also showed interest in working in manufacturing as a CNC operator. During the interview, six of nine participants indicated that if the environment and machine in manufacturing was accessible, they would want to apply for a job as a CNC operator.

Discussion

During the testing, wheelchair users performed 10 tasks related to loading/unloading material, using the control panel, changing a dull tool, and measuring machined parts, on a full-size FVMC mock-up set up to represent current design and three

alternatives.

Through the analysis of the results for the current design, we find that touching all upper buttons on the control panel, inserting the tool into the tool holder and loading the tool are very difficult for the wheelchair users. These tasks were very difficult for them, partly because of how the machine and work area were set up. The control panel was too high for wheelchair users to reach. The tool holder was too far from operators using wheelchair, requiring them to reach forward.

Adjusting the position of the FVMC components seems to be a solution to these problems. If ADA regulations are followed, several changes result: lowering the control unit, making sure there is 19"x32" clearance under the working table, and moving out the tool holder. But the machine with these accommodations will interfere with the users who use the machine from a standing position. Data showed if they work in this setting, they have difficulty reaching the lower buttons and typing on the keyboard. The participants with FVMC operational experience reported that it was very uncomfortable to work on the "ADA FVMC"

Another option is to make the FVMC machine adjustable and customized to serve both seated and standing users. Increased space under the working table, inclusion of an adjustable tool holder and a height adjustable control panel can improve the usability of FVMC for people with and without disability. Setting the machine components to the user's preference can enable wheelchair users and able-bodied people to operate the FVMC easily.

Unfortunately, these outcomes are difficult to characterize or standardize. It should be noted that CNC machine operators have a wider range of responsibility than the four

main tasks that were tested. They also need to clean and maintain the machine, and these tasks were not considered in this testing. The testing also not conducted in a manufacturing environment.

The mock up could be adjusted to preferred positions for most of the components, , but two of the participants wanted the working table to be 2 inches lower than the lowest position on the FVMC mock-up. The size of the control panel was fixed, but three (25%) participants wanted the control panel to be smaller so they could reach all the buttons easily. Ten (67%) of them wanted the control panel keyboard to adjust to a horizontal position or tilt. Typing on the vertical position was very uncomfortable for most of the people.

Making the FVMC accessible for wheelchair users also benefits able-bodied people. All of the five able-bodied subjects preferred to work with FVMC sitting down. Even during the testing, 3 out of 5 subjects (60%) felt tired when they were interacting with the FVMC mock-up standing up.

At the beginning of the study, the researcher expected to recruit ten wheelchair users with T10 or lower Spinal Cord Injury (SCI). This goal was not reached due to difficulties recruiting subjects, and the results were impacted. Three of the subjects had higher level injuries, and as a result, had very weak hand function, but all of them can grasp more than 3 lb small piece materials. . Their reach range is limited,

CHAPTER 5

DESIGN SCENARIOS EVALUATION

Research Question

RQ1. What are the design ideas for making the FVMC easy to use for wheelchair users and people without disabilities?

RQ2: Given several design ideas, which machine design and environment setting is more compatible for wheelchair users and people without disabilities?

Methods

Design scenarios, also known as design concepts, incorporate operational requirements of FVMC and they utilize current and future technologies to develop a safe and efficient work environment for wheelchair users and other people. These scenarios are synthesis of design and technology to offer best FVMC work environments for tomorrow. Evaluation of thesis scenarios will incorporate user perspective and suggest design improvements.

The process of my study was as follows:

The first step was to perform research and needs analysis; where the problem was identified. This step was finished and described in Chapter 3-preliminary research.

The second step was 3D prototype making.

In the third phase, the design concepts and prototype design were evaluated

Prototype of Design Scenarios

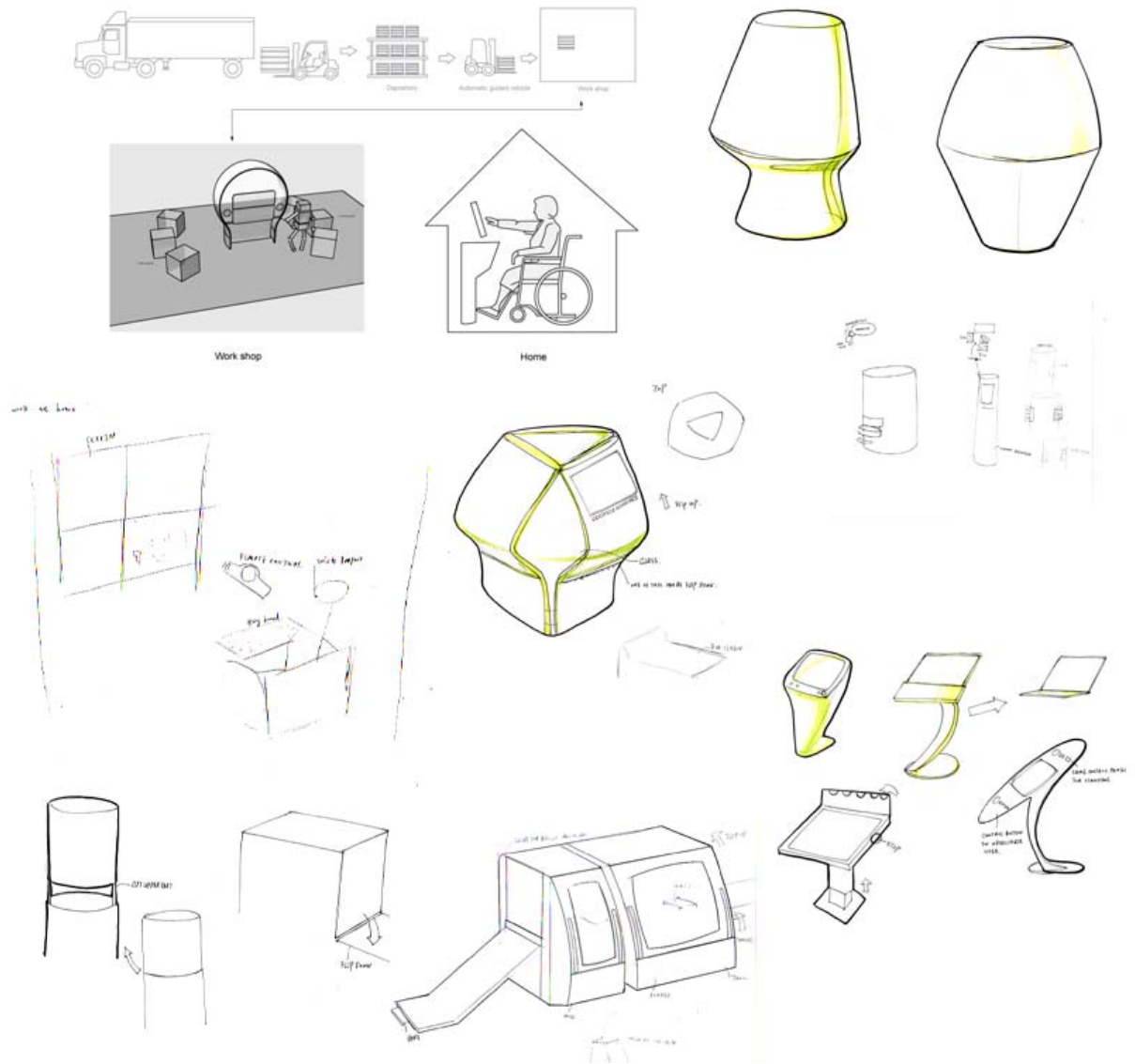


Figure 28: Design Sketches

. Based on the insights from preliminary study, some design concepts (Figure 28) were generated at the beginning. These concepts were reviewed in the thesis studio. At the end two new design of FVMC were developed to be design scenarios (Figure 29,

Figure 31)



Figure 2929: FVMC Concept in Design Scenario 1



Figure 30: FVMC Concept in Design Scenario 2

Features of design scenarios were categorized and described as below:

Features of Design Scenarios:

Scenario 1

Machining components and work area arrangement

- Cutting tool cart, raw material and machined part bin, main machine, control unit arranged in an arc for easy accessibility (Figure 31).
- Open space under the work surface, easier for wheelchair turn around to reach everything they need.
- Measuring tools (e.g. caliper) arranged in a touch-open drawer.



Figure 31: Machining Components and Work Area Arrangement in Scenario 1

Load/unload Material

- Push button at ① to control window up and down (Figure 32)
- Push button at ① to start machine. When machine starts working, window shuts down automatically
- Material arranged in a bin near to main machine (Figure 33)



Figure 32: Control Buttons and Material Bin in Design Scenario 1

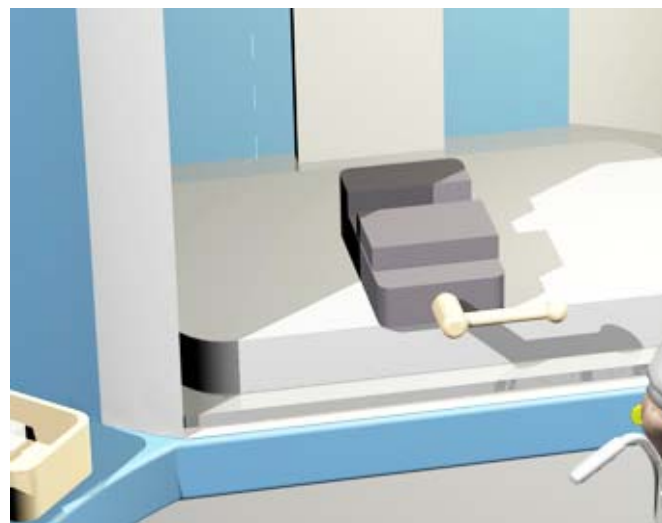


Figure 33: Vise and Machine Table on Design Scenario 1

- Vise stay on the position close to the user (Figure 34).
- When machine starts, vise will slide inside with machine table automatically
- Vise handle arranged inside the touch open drawer on operator's right side

Operate the control panel

- Control panel work functions as a desktop, easier for operator to adjust height and angle (Figure 35)
- Touch screen simplifies the control panel and reduces the size of control panel.
- Start and stop machine by pushing button on the main machine

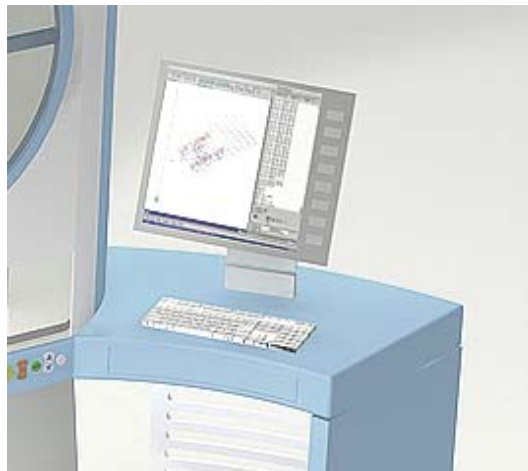


Figure 34: Control Unit in Design Scenario 1

- Tool arranged in a height adjustable table with open space underneath (Figure 35)
- “Tool in/out” button was arranged on the front of tool holder, When the operator changing the dull tool. He can hold the tool while pushing button above tool

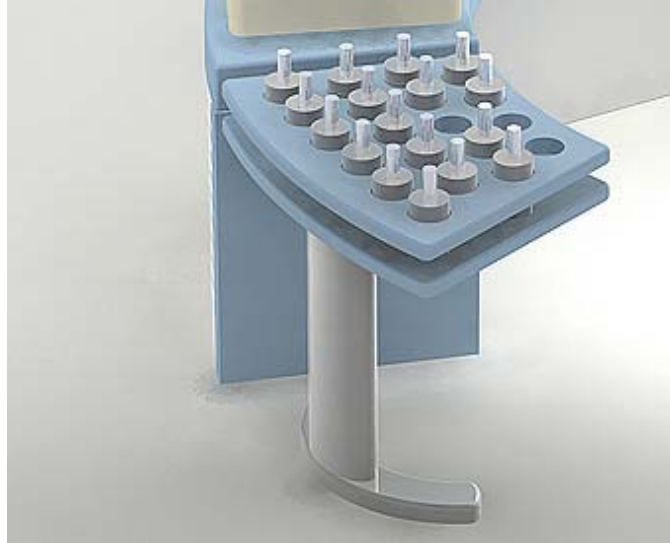


Figure 35: Tool Arranged in a Height Adjustable Table with Open Space Underneath

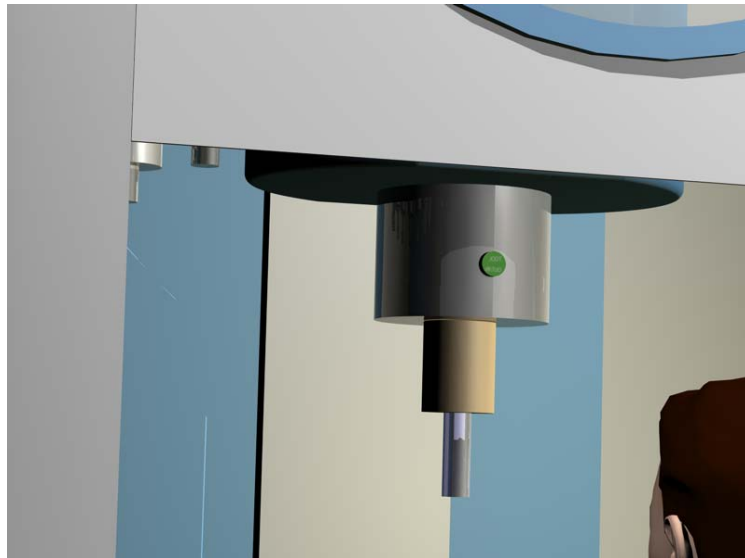


Figure 36: “Tool in/out” Button Was Arranged on the Front of Tool Holder

Measure machined part

- Measuring tools available in the touch-opened drawer near main machine
- Machined part slides out with machine table, easier for the operator to measure it



Figure 37: Machined Part Slides out With Machine Table

- *Other*

- Rotated brush keeps window clean (Figure 38)



Figure 38: In Design Scenario 1, Rotated Brush Keeps Window Clean

Scenario 2

Machining components and work area arrangement

- Wireless control unit functions as a work station
- Work station separate from main machine (Figure 39)
- Mobile work station can be easily repositioned
- Measuring tool (e. g. caliper) arranged in work station

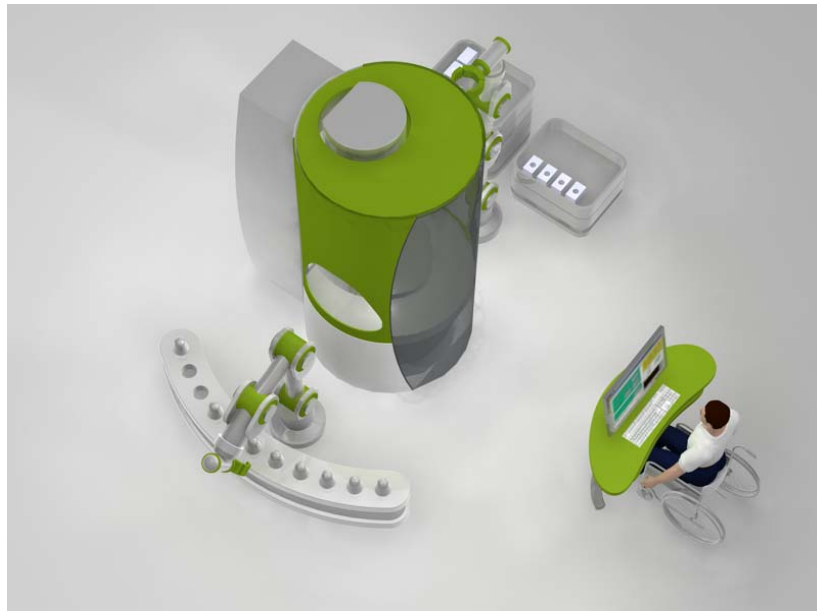


Figure 39: Machining Components and work Area Arrangement in Design Scenario 2

Load/Unload material

- Windows open from both side of machine (Figure 39), this design prevent frying chips hit the operator.
- Windows open or close controlled by work station
- Sensor mounted to the window, if robot near to it, will open automatically,

when machine start window will stay close

- Material arranged in a box on the floor (Figure 40), easy for fork truck to remove it.



Figure 40: Windows Open from both Side of Machine



Figure 41: Material Arranged in a Box on the Floor

- Program control robot arm to load raw material (Figure 41)
- Vacuum table helps tighten raw material



Figure 42 : Program Control Robot Arm to Load Raw Material.

Operate the control panel

- Control panel functions as work station (Figure 43); it is height and angle adjustable.
- Mobile work station can be easily repositioned
- Touch screen simplifies the control panel and reduces the size of control panel.
- Start machine on the workstation using remote control technology, machine will automatically stop if any damage happens
- Operator supervising the work process on the screen, through internal camera



Figure 43: In Design Scenario 2, Control Unit Functions as Work station.

- *Change dull cutting tools*

- Tools arranged easier for robot to pick up the right tools
- Program controls robot arm to replace dull tools (Figure 44)



Figure 44: Program Controls Robot Arm to Replace Dull Tools

- *Measure machined part*

- Measuring tools available in the work station (Figure 45)
- Operator measure machined part on his knees next to the material bins (Figure 46)
-



Figure 45: Measuring Tools Available in the Work Station



Figure 46: Operator Measure Machined part on His Knees

-Other

- Water jets on the top to keeps glass clean

Evaluation

Design scenario evaluation and scale used

A Design Scenario Evaluation Form is conducted to compare the usability of these designs. The subjects were asked to rate their satisfaction with each design after the experiment. Figure 47 shows a part of the Design Scenario Evaluation Form.

Corresponding to four main tasks subjected in the full size FVMC mock-up, the first section of the questionnaire is “Load/unload material”. Three statements listed in this section. A likert scale measured the subjects’ attitude and opinion to the design scenario. There are 5 scales for each question. The scale is 1 to 5: 1= strongly disagree, 2= disagree, 3= not sure, 4= agree, and 5=strong agree. The higher score means the design is more efficient, satisfaction and safer. The design scenario was evaluated based on four main tasks: loading/unloading material, operate on the control panel, changing dull tool, measured machined parts. Whole Design Scenario Evaluation Form was list in Appendix

In order to compare the design scenario with existing FVMC, the subjects also asked to evaluate existing FVMC with accommodations.

Load/Unload Material		1	2	3	4	5	
● This machine will enable me to load/unload material quickly.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to load/unload material easily.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to load/unload material safely, it will not cause fatigue, uncomfortable and injury.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree

Figure 47: Part of Design Evaluation Form

After subjects finished the questionnaire, an interview was conducted, questions

like, which machine design do you like? Why? Do you have any suggestion about the machine design?

Result

Total score for design current machine with accommodation was 718; Design scenario 1 was 773. Design scenario 2 was 735. Scores collected from subjects were listed in the Appendix J.

Independent samples t-tests were run to compare the scores. There is no statistically significant difference between each user group and there is no significant between each scenario. But most people (9 of 15) indicated that they prefer the design of scenario 1. 5 of the subjects (34%) prefer the design of scenario 2. 1 subjects refer she is satisfied with the existing machine; the reason is she likes to finish every tasks by hand. In Figure 51, 52 and 53, we can see there is not quite different between each scenario. So the verbal data below is more important for this study.

Verbal data is more important for analysis

Notes were taken during the interview and listed in Appendix K. The following themes were explored:

Verbal data:

Scenario 1

Problems:

- Too much space around the operator, he still need to move (People without

disabilities)

- The handle for tighten vise is very difficulty using

Benefits:

- User has more control on the machine
- “most used” buttons is good idea, “design of buttons is perfect”
- Enough space for working is good, the arrangement of supply is convenient for the operator

Suggestions:

- Should make next generation of FVMC easier to change, because company don't want to buy new machine
- Put the small box of material onto the bigger box, so the other worker can help to remove the finished part, once or twice a day only.
- Should have Closer space. Stay in one place will be easier (wheelchair users)

Scenario 2

Problems:

- “I don't trust robot arm, machine will go crazy to hit the person”
- If the robot has problem, the production will be stopped, because the wheelchair user can't fix it (wheelchair users)
- Reach the machined part will get hurt, sometimes the material is heavy, and reach down is a little difficult for wheelchair user (wheelchair users)
- Changing the tool will be dangerous, if the operator make mistake the machine

will start by accident

- What the operators are doing is not connected with what they need to do.

Participation is much less. The less effort is required the more bored

- Using robot arm is easier, but not faster,

Benefits:

- Automatic looks cool
- Operators can control more machines
- Machine with robot arms eliminate all physical demands on operators
- Using computer is much easier for wheelchair user (wheelchair user)

- Suggestions:

- The control unit should be moved far away from the robot arms
- If the operators don't need to move the material would be better, sometime the material is very heavy. Build the tray to elevate up material for the operator to pick up the material or using robot to arm pick up the material (wheelchair user)
- When the operator move toward the machine, the machine should stop.
- Need work surface, when the operator (wheelchair user) check the result, put parts on the legs is not safe.
- workstation should be closer to the machine (wheelchair user)
- Robot quicker than human, but safety sill a big issue

Discussion

The results showed that, the evaluation scores of FVMC design scenario have no statistically significant difference. But subjects comments shows 1 was the best one, in terms of both safety, easy and satisfaction.

Because of the time and technology limitation, the design is showed in the format of 3D video, compare to physical mock-up; it is a little difficult to judge from animations. So the result is based on the subjects' imagination.

Many subjects afraid of work with robot, there are two main reasons 1. Robots are not safe for them sometimes the robots “go crazy”. 2 The fabricating process will stop if the robot system has problems. Subjects especially wheelchair users concerned about they might need to learn how to fix it and the robot arms are also difficult for them to access. But work with robot arms also has benefit; it can reduce the “physical demands on the operator”. During the work flow, the FVMC operators don't have to worry about the “reach” issue, the operational job will be easier for them.

Scenario 1 is a good design for them, there are one main reason, 5 of 9 wheel chair user subjects implied they prefer stay in the same place. Only reach, without move will be easier for them. They like the arrangement of work area, it is well organized and the arrangement of button is easier for them. “Half automatic” machine would be better for now, because people will have more control over the machine. And although scenario 1 has lower level then scenario 2, but it is more accessible for the wheelchair user, and also make a big improvement of current designed FVMC 15 machine.

CHAPTER 6

DESIGN GUIDELINES AND CONCLUSIONS

Research conclusions:

CNC machine widely used in manufacturing environment, the physical requirement for the machine operator is significantly reduced. There is a potential for wheelchair user to get a job in manufacturing environment as a CNC operator, but there is no study showed that wheelchair users can work on CNC machine safely, easily, and efficiently. In a case study of FVMC 15, barriers for wheelchair users were identified.

Loading material, changing tool, operating on the control panel, checking machined parts is most important tasks for the FVMC 15 operators, but most of these tasks are all difficult for the wheelchair users. Most of the wheelchair users could not perform the tool loading task using current machine designs, because it requires the operator to reach two sides (holding the tool and operating a button with the other hand). Wheelchair users lost their balance and had safety issues when performing this task. Some wheelchair users did not have good abdomen muscles, so they were not able to finish this task. Operate on the control panel also difficult for them. Because, current designed FVMC 15 control has a fixed control panel and it is in a very high position. Upper button is out of the wheelchair users' range of reach. Screen on the control also above the eye height of them. Looking up for a long time also cause fatigue. Typing on the control is not only difficult for the wheelchair users but also for people without disability. Data show that adjusting the position of FVMC components and increasing space under the

working table can overcome the barriers on current designed FVMC machine for wheelchair users.

The performance and preference between the wheelchairs is quite different. People without disabilities can work on the current designed FVMC 15 very well but if the machine design is only concerned about wheelchair user, people without disability will have their “barrier” to use this machine. Customized FVMC 15 is the best way to accommodate both user groups. Customizing the FVMC will not only benefit the wheelchair users. People without disability also can take advantage of the adjustable FVMC. Working on the manufacturing for a whole day standing up is very tired for everybody. During the testing overwhelming majority of people without disability indicated that they prefer sitting down to do the work.

In the testing some components of the mock-up is fixed. It is difficult to test out the best solution for the operator. For example, some wheel chair users want to tilt the control panel. But in the study the size of control panel is fixed. Assuming that design based on the FVMC mock is best solution for the development of universal CNC machine. Two design scenarios was generated and tested afterward. The design scenarios are more like a near future concept of FVMC design. Analysis the score on design evaluation form, there is not statistically significant different between two design scenarios and current designed FVMC with accommodations. The verbal data is more valuable for this study. Most of the subjects like the “half automatic” FVMC best. The arrangement of the work space is good for the wheelchair user to reach everything they need. Reduce unnecessary of the operator. In this study, also find out people are not quite ready for the computer controlled robot arm. Safety still a big issue needs to be concern

in the future. In this study also find that wheelchair users prefer to work, they also consider about working in the manufacturing environment in future.

Guidelines

Based on the information gathered in earlier steps of this process, a set of design guidelines was compiled for developing a guide for CNC machine designer. Although my thesis will not test these guidelines in manufacturing environment, the guidelines will provide a valuable starting point for the planning of future FVMC machine design. And this not only limited in the Fadal Vertical Machine 15. Any CNC machine has the similar function and size also can use this design guideline.

- High of the machine table should be ranged from 72 cm-82 cm. because of power wheelchair might use the hand control device, and the machine table should have enough thickness to support the machine, so the machine table will be higher than the traditional working table. If there is mechanical difficult the table should be fixed, the high can be 79cm.
- Enough under the machine table on the main machine is necessary, width at least 112cm and depth at least 50 cm. Data provided by ADA regulation is not enough for the FVMC design. Loading/unloading material requires operators to turn around.

- The control panel should be height adjustable. From the center of control panel to floor, the adjustment range at least from 61cm to 118cm. Consider that the FVMC 15 control panel is very big. It can't be too low. Otherwise it will interfere with wheelchair users.
- The control panel should be able to be adjusted along the edge. From the center to the pivot of the control panel, the adjustment range at least from 63cm to 83cm. The control panel too far or too close to operators will cause uncomfortable. If the control panel is too far, operators need to move around the workspace. If the control panel gets too close to the operator, there is not enough room for the arm movement. So make sure the adjustment range of control panel is enough.
- Window opening on the machine wider than 106 cm is better at, least 102 cm.
- The tool holder should be able to be adjusted in and out. From the center to the tool holder to the edge of machine table, the adjustment range is at least from 17cm to 53.8 cm. Loading tool is one of the most difficult part for wheelchair users. It is difficult for them lean forward. The tool holder should be
- When the operator stop the machine, prepare to change the tool. The tool holder should be stay in the position 101cm-153cm from the floor. When the operators insert the cutting tool to the tool holder, they might need to check if the tool is loaded correctly.

- Control may need to be tilt or it may have a flat keyboard for typing; also need a hand rest around the keyboard area.
- Tilted vise may help wheelchair user to measure the material, and see the scale on the measurement tool more clearly.
- The size of control panel should not be larger than H70 x W60 x D25cm (size of FVMC 15). It will be difficult for wheelchair users to reach the upper buttons.

Use guideline listed above to modify or improve current FVMC 15 or other type of CNC machine. Following with these guidelines, a CNC machine with these accommodations can be used by wheelchair user and people without disability.

If there is a chance to have enough budget to develop a new FVMC machine, Guidelines listed below might be helpful for generate a better concept. Figure 54 shows a sample of new FVMC design.

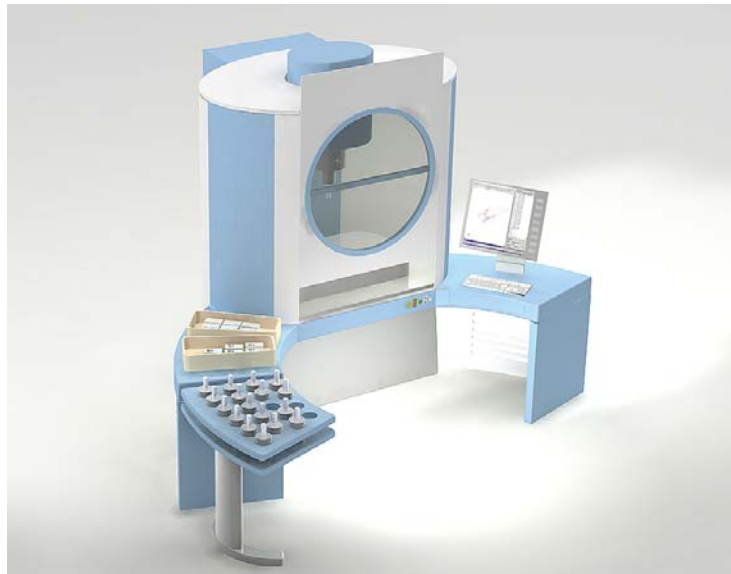


Figure 48: FVMC Design

- The size of control panel should not be larger than H70 x W60 x D25cm (size of FVMC 15). It will be difficult for wheelchair users to reach the upper buttons.
- The work area arrangement should be more compact. Make sure there is enough space for users to turn around. And without moving they can reach the material bins, control units and measurement tools.
- There should have enough space under the work surface for wheelchair users'

movement.

- Control panel can function as desktop and use touch screen. Using touch screen will reduce the size of control panel. Movement between the machine and computer room will be reduced.
- Start/stop button and other high frequency used buttons, should be arranged on the main machine that is easier for the operators to reach.
- There should be an automatic blush on the window to keep it clear.

Limitations and future work

The next step of this study is to make a full size mock-up of design scenario 1, recruit more subjects using wheelchair and able-bodied operators with CNC operational experience, use the same method in chapter 5, to improve the design.

There are other work activates such as installation, adjustment, maintenance, cleaning, repair and machinery transportation involved in the FVMC operation workflow. This activates can be take into account into next texting.

Wheelchair user is a group of people with disability. Universal design of the CNC machine should be able to accommodate wider range of people with disability. For example, next step of testing can involve people with vision impairment.

Fadal Vertical Machining Center, is a brand of vertical machining center, vertical

machining center is one type of CNC machine. How to compile a design guideline that can be able to use by all CNC machine designers is a big issue for future study.

Additionally, helping CNC machine designers, developers and CNC machine manufacturers understand the benefits of universal CNC machine design, and testing the design guideline between them are also important work in the future.

APPENDIX A:

INTERVIEW QUESTIONNAIRE

1. What type of CNC machines are you working with? Please mark the one you used more often
2. What kind of product or part are you making?
3. Do you use any hand tools to help your work? What are they? Which ones are used frequently?
4. How long have been working as an operator?
5. What level of education are you in?
 - a) High School
 - b) Undergraduate
 - c) Master
 - d) Other
6. Where did you get the working skill?
 - a) In school
 - b) In training center
 - c) In the working place
 - d) Other_____
7. How long did you take to be an operator? Do you have any certification?
8. What is your job duty?
9. Do you work independently?
10. How many workers work on this machine? What are shift timings?

11. What materials are you using? How heavy how big they are?
12. Can you describe your tasks in detail including movements, reach etc.
13. How long do you work per day, how many days do you work per week?
14. How long will you take a break?
- a) 10 minutes
 - b) Half hours
 - c) One hours
 - d) 90 minutes
 - e) 2 hours
 - f) Other_____
15. How long does it take to finish a part?
16. Which task is the most difficult for you?
17. Is there safety issue in your working environment? Did you get any injury when you were working? Did you hear any body get injury when operating with this machine?
18. Do you have any preparation for the unplanned event?
19. What do you think about People with low vision or people with wheel chair do this job?
20. What is your suggestion for people with disability who interesting in becoming a CNC machine operator?

APPENDIX B

NOTES FROM INTERVIEW

- Most of the CNC operator graduated from the technology school, they get their training from the school and when they started to work they also need to get training from the manufacturing.

- Their job duty is programming, setup the machine, controlling quality, clean and maintain machine, but it depends on the size of manufacturing.

- The operators I interviewed use to working in small manufacturing. They need to work independently to finish most of their work.

- All of them work 8 hours a day in the manufacturing environment; only take a break 1 hour for lunch, and 15 minutes in the afternoon.

- They use hand tools quite often, such as screw driver, Allen-wrench to help with the work.

- After the machine set up, running CNC to machining a part only takes 5 minutes, so they repeat the same activates more than 50 times a day.

- Programming is the most difficult part for most of them.

- Loading/unloading material and clean are the tasks cause uncomfortable.

- There are some accident happened in their experience. One of them hit by the flying material and the eyes hurt. Two of them also get hit when moving the heaving material.

- They also concern about the damage on the machine, because fixing the CNC machine is expensive. Cutting into the table, damage on the tools, windowing broken by

the moving vise happened to the FVMC.

- Lean forward into the machine and standing for 8 hours cause their fatigue.
- People are interested in working in manufacturing, because they are interested in making “stuff”.
- All of them think the CNC operator is a difficult job for wheelchair user. Reach and observation is the big barrier for people with wheelchair.
- Some operators suggest that the future machine should be more compact, combining more function in a machine.

APPENDIX C

NOTES FROM OBSERVATION

- FVMC is design for the operator work standing up, many tasks required the operator reaching high, reaching forward, reaching two side.
- Sometimes the operator forget to shut down the window it will cause accident.
- Lubricant and coolant will make the window blur and difficult for the operator to supervise the working process.
- Loading/Unloading material, Operate on the control panel, check the quality of the machined parts are the most important sequences. Changing dull tool is another task needs to finish by the operator indecently.
- Using the mouse on the control panel is uncomfortable.
- Difficult to see the scale on the switches, some of switches, knobs and buttons look quite similar, easy to be misused by the operator; label on the frequently used buttons wear off.
- The tool carts disturb the operator's movement.

APPENDIX D

IRB CONSENT FORM FOR MOCK-UP TESTING

Georgia Institute of Technology

Project Title: Design for Wheelchair Users in Manufacturing Environment

Investigators: Abir Mullick, Xiaoyi Ye

Consent title: Evaluation of a CNC Machine Model

Research Consent Form

You are being asked to be a volunteer in a research study.

Purpose:

The purpose of this study is:

The purpose of this project is to test a non-operational model of a CNC machine with wheelchair operators as well as able-bodied people. This will help identify operational problems, design limitations and how to redesign a CNC machine that is safer and easier for everyone. A total of 30 people will participate in the study, which will include 15 wheelchair users and 15 able-bodied people.

Procedures:

If you decide to be in this study, you will be asked to do the following:

- Fill out a demographic questionnaire that describes your background and experience. This should take about 10 minutes. In our view there are no personal or

sensitive questions but should you feel there are, you are free to not provide information.

- Measure your stature, eye height, knee height, shoulder height, elbow height and arm length using standard tools such as a flexible tape measure or caliper. The tools should not cause you any discomfort and this will takes 10 minutes.
- Receive instructions about the tasks we will expect you to perform. Please know that you are not obligated to perform the tasks if they are difficult for you and this will not affect receiving honorarium. This will takes 15 minutes.

Perform tasks are associated with the use of a CNC machine; example pretend to place material, control operation, measure material and change the tool. You will perform the tasks three times. After performing the tasks, you will be asked to fill out a questionnaire about your experience of using the model. This process will take about one hour.

- At the end of the study, you will be asked about the use of the CNC model, and about the three set-ups.

The study will take about one hour and 35 minutes. The act of operating a CNC model will be videotaped using overhead cameras, so the information can be reviewed at a later date.

Risks/Discomforts

The following risks/discomforts may occur as a result of your participation in this study:

During this study, you should not be at risk. You will stay in the test room while you

participate, and a researcher will be there to help you. Since you will be performing basic tasks, we don't expect you to get hurt. We will maintain a safe working environment and cover sharp corners on to prevent any injury. You are free to refuse to answer any questions, and remove yourself from the study at any time with no penalty.

Benefits

The following benefits to you are possible as a result of being in this study:

There are no direct benefits to you as a result of being in this study. We hope that your involvement in this research will help us design better and safer manufacturing environment for all people.

Compensation to You

You will be compensated \$35 for your time, even if you decide to stop early.

Confidentiality

The following procedures will be followed to keep your personal information confidential in this study. The data that is collected about you will be kept private to the extent allowed by law. To protect your privacy, your records will be kept under a code number rather than by name. Your records will be kept in locked files and only study staff will be allowed to look at them. Your name and any other fact that might point to you will not appear when results of this study are presented or published.

Because of your privacy concerns, we plan to note your name only in the consent form and not in any other research records. We will use a code to track your records. The

research notes will be destroyed within 3 years after the interview. Videotapes of you will be used only by the researchers, and the tapes will be stored in the researcher's office in a locked file cabinet. The tapes will be destroyed three years after the research is complete.

The individuals working on this project will be instructed about the importance of confidentiality and how to maintain it. All research and background materials will be in the custody of the Principal Investigator and stored in a locked file.

To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology IRB may review study records. The Office of Human Research Protections may also look at study records.

Costs to You

There is absolutely no cost to you.

In Case of Injury/Harm

If you are injured as a result of being in this study, please contact Xiaoyi Ye at telephone (402) 304-5951. Neither the Principal Investigator nor Georgia Institute of Technology has made any provision for payment of costs associated with any injury resulting from participation in this study.

Subject Rights

- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.

- You have the right to change your mind and leave the study at any time without giving any reason, and without penalty.
- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

Questions about the Study or Your Rights as a Research Subject

- If you have any questions about the study, you may contact Xiaoyi Ye at telephone (402)304-5951
- If you have any questions about your rights as a research subject, you may contact Ms. Melanie Clark, Georgia Institute of Technology at (404) 894-6942.
- If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

Subject Name

Subject Signature

Date

Signature of Person Obtaining Consent

Date

APPENDIX E

PROTOCOL OF FVMC MOCK-UP TESIGN

You are being asked to pretend operating a non-working CNC machine. Kindly do the following:

- Pick up the block located on your left and move the block.
- Place the block on the table marked X.
- Rotate the handle at Y to tighten the vise on the table (Figure 1).
- Pretend to operate the control panel by touching all the buttons to your right.
- Confirm you can see the screen control panel by reading the sentence on the “screen”
- Confirm you can see the tool to front of you by identifying its color.
- Use calipers to measure the width and length of the block.
- Pick up the cylinder at the desk on your left and position it in the hole located above the block.
- Hold the tool and touch the red button on the control panel.

You will perform this three times. The first time you will work on the CNC model setup 1. The second time you will work on the CNC model setup 2. The last time you can ask researcher to adjust the model to your preference.

You will be asked to fill out a questionnaire about your experience of using the model.

APPENDIX F

BACKGROUND SURVVEY

Code (To be filled by researcher)_____

BACKGROUND QUESTIONS

Date: ____/ ____/ ____

Your Information

Education:_____

Age: 18-30 30-40 40-50 60+

Gender: Male Female

a) Do you have a disability, please briefly describe?

b) Do you use any assistive technology?

c) Do you work outside home? Yes No

d) What is your current level of employment

-Employed full-time

-Employed Part-time

-Unemployed

e) If you are employed, what is your current job title?

f) If you unemployed is it due to:

-Poor design of surrounding

-Poor machine design

-Other_____

g) Do you have any working experience in manufacturing environment?

h) Would you want to work in manufacturing environment as a machine operator?

APPENDIX G

FVMC MOCK-UP EVALUATION FORM

Tasks	Can't Do It	Very Difficult	Difficult	Just Right	Easy	Very Easy
Pick up the block located on your left and move the block	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Place the block on the table marked "VISE"	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Rotate the handle to tighten the vise on the table	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Tasks	Can't Do It	Very Difficult	Difficult	Just Right	Easy	Very Easy
Use measurement tool to measure the width of the block	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

■ *Machine Components Evaluation Form*

The table on the machine is	Too High	Just Right	Too Low
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The window opening is	Too Narrow	Just Right	Too Wide
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

■ *Comments*

Figure 49: FVMC Mock-up Evaluation Form Part 1.

Tasks	Can't Do It	Very Difficult	Difficult	Just Right	Easy	Very Easy
Touch all upper buttons	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Touch Lower buttons	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Touch keyboard	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Read the sentence on the "screen"	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

■ *Machine Components Evaluation Form*

The control panel is	Too High	Just Right	Too Low
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The control panel is	Too Far	Just Right	Too Close
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

■ *Comments*

Figure 50: FVMC Mock-up Evaluation form part 2.

Tasks	Can't Do It	Very Difficult	Difficult	Just Right	Easy	Very Easy
Pick up the cylinder at the desk on your left and position it in the hole located above the block	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Hold the tool and touch the red button on the control panel	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Machine Components Evaluation Form

The tool holder is	Too High	Just Right	Too Low
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The tool holder is	Too Far	Just Right	Too Close
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The control Panel is	Too Far	Just Right	Too Close
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Comments

Figure 51: FVMC Mock-up Evaluation form part 3.

APPENDIX H

IRB CONSENT FORM FOR DESIGN SCENARIO EVALUATION

Georgia Institute of Technology

Project Title: Design for People with Disability in Manufacturing Environment

Investigators: Abir Mullick, Xiaoyi Ye

Consent title: Evaluation of CNC Machine Designs

Research Consent Form

You are being asked to be a volunteer in a research study.

Purpose:

The purpose of this project is to assess three new designs for a computer-numeric-controlled (CNC) machine. A total of 30 people will participate in the study, that will include 10 wheelchair users and 20 able-bodied people.

Procedures:

If you decide to be in this study, your part will involve:

- You will be asked to fill out a demographic questionnaire that describes your background and experience. Filling out the questionnaire should take about 10 minutes.

After the questionnaire is completed, you will be shown three videos of the new

CNC machines (fig 1, fig 2, fig 3). After each video you will be asked to fill the evaluation form to indicate your response about likes, dislikes and preferences. This process will take about 50 minutes.

Risks/Discomforts

The following risks/discomforts may occur as a result of your participation in this study:

While in this study, you should not be at risk. You may refuse to answer any questions, and remove yourself from the study at any time with no penalty.

Benefits

The following benefits to you are possible as a result of being in this study:

There are no direct benefits to you as a result of being in this study. We hope that your involvement in this research will help us design better and safer manufacturing environment for all individuals

Compensation to You

You will be compensated \$15 for your time, even if you decide to stop early.

Confidentiality

The following procedures will be followed to keep your personal information confidential in this study: The data that is collected about you will be kept private to the

extent allowed by law. To protect your privacy, your records will be kept under a code number rather than by name. Your records will be kept in locked files and only study staff will be allowed to look at them. Your name and any other fact that might point to you will not appear when results of this study are presented or published.

Because of your privacy concerns, we plan to note your name only in the consent form and not in any other research records. We will use a code to track your records. The research notes will be destroyed within 3 years after the interview.

The individuals working on this project will be instructed about the importance of confidentiality and how to maintain it. All research and background materials will be in the custody of the Principal Investigator and stored in a locked file.

To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology's IRB may review study records. The Office of Human Research Protections may also look at study records.

Costs to You

There is absolutely no cost to you.

In Case of Injury/Harm

If you are injured as a result of being in this study, please contact Xiaoyi Ye at telephone (402) 304-5951. Neither the Principal Investigator nor Georgia Institute of

Technology has made provision for payment of costs associated with any injury resulting from participation in this study.

Subject Rights

Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.

You have the right to change your mind and leave the study at any time without giving any reason, and without penalty.

Any new information that may make you change your mind about being in this study will be given to you.

You will be given a copy of this consent form to keep.

You do not waive any of your legal rights by signing this consent form.

Questions about the Study or Your Rights as a Research Subject

If you have any questions about the study, you may contact Xiaoyi Ye at telephone (402)304-5951

If you have any questions about your rights as a research subject, you may contact Ms. Melanie Clark, Georgia Institute of Technology at (404) 894-6942.

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

Subject Name

Subject Signature

Date

Signature of Person Obtaining Consent

Date

APPENDIX I

DESIGN SCENARIO EVALUATION FORM

■ Scenario evaluation scale:

Please assess the machine design and their operations as if you are the operator using it ask any question to better understand its work. Once you have understood the machine, please use the below table to offer design feedback on a ten point scale.

Load/Unload Material

	1	2	3	4	5	
● This machine will enable me to load/unload material quickly.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to load/unload material easily.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to load/unload material safely, it will not cause fatigue, uncomfortable and injury.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree

Operate the Control Panel

	1	2	3	4	5	
● This machine will enable me to operate the control panel quickly.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to operate the control panel easily.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to operate the control panel safely, it will not cause fatigue, uncomfortable and injury.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree

Change Dull Cutting Tool

	1	2	3	4	5	
● This machine will enable me to change tool quickly.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to change tool easily.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to change tool safely, it will not cause fatigue, uncomfortable and injury.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree

Measure Machined Part

	1	2	3	4	5	
● This machine will enable me to measure machined part quickly.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to measure machined part easily.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree
● This machine will enable me to measure machined part safely, it will not cause fatigue, uncomfortable and injury.	Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Agree

Figure 52: Design Scenario Evaluation Form

APPENDIX J

DESIGN SCENARIO EVALUATION RESULT

Scenario Evaluation scale	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Existing machine with accommodations															
This machine will enable me to load/unload material quickly	4	3	5	4	4	4	5	4	4	2	4	3	5	4	4
This machine will enable me to load/unload material easily	4	2	5	4	4	4	5	3	5	3	4	5	4	3	4
This machine will enable me to load/unload material safely	4	4	5	4	4	4	5	2	5	3	4	5	5	3	4
This machine will enable me to operate the control panel quickly	4	3	5	4	4	4	4	4	4	1	5	4	4	4	5
This machine will enable me to operate the control panel easily	5	5	5	4	3	4	4	4	4	1	4	5	3	4	5
This machine will enable me to operate the control panel safely	5	5	5	4	3	4	5	4	4	1	5	5	5	5	5
This machine will enable me to change tool quickly	5	3	4	4	4	4	5	4	4	1	4	3	4	3	4
This machine will enable me to change tool easily	5	4	4	4	4	4	5	3	4	1	4	5	4	3	4
This machine will enable me to change tool safely	5	1	4	3	3	4	5	4	4	1	4	5	3	2	4
This machine will enable me to measure machined part quickly	5	3	5	3	4	5	5	4	4	3	5	2	4	4	4
This machine will enable me to measure machined part easily	5	4	5	3	3	5	5	4	4	4	5	3	4	4	4
This machine will enable me to measure machined part safely	5	4	5	4	4	5	5	4	4	5	5	5	4	4	4

Scenario Evaluation scale															
scenario 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
This machine will enable me to load/unload material quickly	5	4	4	5	2	5	5	2	4	3	4	4	5	4	5
This machine will enable me to load/unload material easily	5	4	4	5	2	5	5	2	4	4	5	5	5	3	5
This machine will enable me to load/unload material safely	5	4	4	5	2	5	5	2	3	4	4	5	4	3	5
This machine will enable me to operate the control panel quickly	5	4	5	5	4	5	5	4	4	2	5	5	5	4	5
This machine will enable me to operate the control panel easily	5	4	5	5	4	5	5	4	4	3	5	5	5	4	5
This machine will enable me to operate the control panel safely	5	4	5	5	4	5	5	5	4	4	5	5	5	4	5
This machine will enable me to change tool quickly	5	5	5	4	2	5	5	4	4	3	5	4	4	3	5
This machine will enable me to change tool easily	5	5	5	4	2	5	5	3	4	3	4	5	4	3	5
This machine will enable me to change tool safely	5	5	5	4	2	5	5	4	3	3	4	5	4	4	5
This machine will enable me to measure machined part quickly	5	5	5	5	5	5	5	4	3	3	4	3	4	3	5
This machine will enable me to measure machined part easily	5	5	5	5	5	5	5	3	3	3	5	4	4	3	5
This machine will enable me to measure machined part safely	5	5	5	5	4	5	5	4	4	3	5	5	4	3	5

Scenario Evaluation scale															
scenario 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
This machine will enable me to load/unload material quickly	5	5	5	5	5	4	5	5	3	3	4	5	5	2	3
This machine will enable me to load/unload material easily	5	5	5	5	5	4	5	5	3	4	5	5	5	5	4
This machine will enable me to load/unload material safely	3	5	5	5	5	4	5	5	4	4	5	5	5	5	4
This machine will enable me to operate the control panel quickly	5	5	5	5	5	4	5	5	4	2	5	5	5	2	3
This machine will enable me to operate the control panel easily	5	5	5	5	5	4	5	5	4	3	5	5	5	5	3
This machine will enable me to operate the control panel safely	3	5	5	5	5	4	5	5	4	4	5	5	5	5	3
This machine will enable me to change tool quickly	5	5	5	5	5	4	5	5	3	4	4	5	5	3	4
This machine will enable me to change tool easily	5	5	5	5	5	4	5	5	3	4	5	5	5	5	4
This machine will enable me to change tool safely	1	5	5	5	5	4	5	5	4	4	5	5	5	5	4
This machine will enable me to measure machined part quickly	5	3	5	5	4	5	2	4	3	2	3	3	4	2	4
This machine will enable me to measure machined part easily	5	3	5	5	4	5	3	4	3	2	4	5	4	2	4
This machine will enable me to measure machined part safely	1	4	5	5	4	5	3	4	4	2	5	5	4	3	4

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